

ACTIVE EXPERIMENTS IN SPACE

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16. Abstract Space is a unique laboratory for studying various physical phenomena. Utilizing plasma fluxes and beams of charged particles, it is possible to actively intervene in the life of the magnetosphere by producing on command from Earth various geophysical phenomena. On the other hand, active intervention in the phenomena occurring in the magnetosphere is most conveniently carried out in laboratory experiments with an artificial magnetosphere. The booklet described various active experiments in the magnetosphere, including laboratory studies.			
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During the long history of the growth of space science, information on objects investigated was obtained exclusively by observations. In this space science differed from other sciences where the main role as a rule was played by experiments, that is, active influencing the course of natural physical processes. The transition from observations to experiments often led to scientific discoveries and changes in our old views on a particular phenomenon. For example, all our ideas about the atomic nucleus are based on experiments in which fast particles interact with nuclei. The basis here was laid by the famous experiment of Ernest Rutherford. No careful observations of radioactive decay or mass-spectroscopic measurements could even approximately approach present-day models of the atomic nucleus.

Before the launch of the first artificial Earth satellites the situation in space physics was similar to the situation in the science of the structure of matter before E. Rutherford's experiment. The situation did not radically change even after the first spacecraft flights. Instruments installed on satellites and rockets made it possible to measure the characteristics at a given point, but the methods remained passive, that is, the effects associated with perturbation of the medium essentially were not studied.

At the present time, active experiments are developing mainly along the direction of producing in the magnetosphere plasma formations of different types and studying the effect of these formations on the geomagnetic field (precipitation of particles causing artificial polar lights and the development of other geophysical phenomena). Several experiments in space have already been completed, while others are in the stage of preparation or discussion. Before beginning to look at them, let us dwell briefly on several general-physical problems necessary to our understanding of the processes occurring in the magnetosphere.

Plasma in a Magnetic Field

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The Earth's magnetosphere is filled with plasma, therefore the laws of plasma physics are the main laws underlying processes in near-Earth space. Often plasma is called the fourth state of

* Numbers in the margin indicate pagination in the foreign text.

matter, since its properties differ from the properties of gases, liquids, and solids. Above all, plasma is like gas, but it cannot be identified with gas of ionized particles. In an ordinary gas, the interaction between particles occurs only briefly, when they fly toward each other at short distances. The rest of the time gas particles move rectilinearly, without sensing the fields of other particles. In plasma each charged particle interacts continuously at once with the fields of numerous particles surrounding it and the particle trajectory is continuously changing its curvature. This kind of motion is due to the long-range action of coulombic forces (the potential of a charged particle drops off inversely proportional to the distance from it). For an ionized gas to acquire the properties of a unified entity bound by self-consistent electric fields, it is necessary that the radius of the sphere occupied by ionized particles exceed some critical value, which we call the Debye radius λ_D . This value depends on the concentration of the charged particles n and on temperature T and determines the maximum distance by which positive (ions) and negative (electrons) particles can be separated due to thermal motion:

$$\lambda_D = \sqrt{\frac{\kappa T}{4\pi n e^2}}.$$

If we introduce an outside charge into a plasma, the plasma's 15 charged particles are regrouped so that the electric field of the introduced charge will be entirely compensated by a distance greater than the Debye radius.

In spite of the fact that plasma particles are bound together by a self-consistent field, sometimes in analyzing plasma behavior it is sufficient to trace the trajectory of an individual charged particle along external electromagnetic fields. This method of studying plasma is called single-particle approximation. A single-particle approximation is valid when the motion of ions and electrons in the external fields does not lead to the accumulation of charges of the same sign in specific areas of space. Or, as it is stated, no polarization electric fields are produced.

Let us examine the most typical cases of the motion of charged particles in combined electric E and magnetic B fields. The force

$$F_m = v \times B/c,$$

perpendicular to the particle velocity and the direction of the magnetic force lines acts on a particle that is in a uniform magnetic field. Motion under the action of force F_m can be

divided into two independent motions: translational motion at constant velocity $v_{\parallel}$ along their force line and rotational motion along a surface having the radius $\rho = mv_{\perp} c / eB$ ("Larmor" radius). Here m and e are the particle mass and charge, respectively, and $v_{\perp}$ is the velocity component perpendicular to the magnetic force lines. The period T_m -- the revolution of a particle around a force line -- depends only on the magnetic field intensity:

$$T_m = \frac{2\pi mc}{eB}.$$

Thus, in a constant and uniform magnetic field a particle will move along a spiral whose axis coincides with the force line, and the particle displacement across force lines occurs only due to collisions.

A remarkable feature of the behavior of a particle in a magnetic field is the conservation of the quantity $\mu_{\parallel} = mv^2 / 2B$, that is, the conservation of the ratio of the rotational-motion energy to the magnetic field intensity. On the other hand: μ is the magnetic moment of the circular current induced when a particle travels along a circle in a magnetic field. The magnetic moment μ is often called the adiabatic invariant. The adiabatic invariant is not conserved for very rapid changes in field compared to T_m or when significant field inhomogeneities are present at distances of the order of the Larmor radius. /6

From the conservation of the adiabatic invariant it follows that a particle in a magnetic field can be regarded as a magnetic dipole exhibiting velocity $v_{\parallel}$ directed along the force lines. As we know, a dipole in a magnetic field is acted on by a force proportional to the scalar product of the magnetic moment by the field gradient and repelling it from the domain of a strong field. We will try to imagine how a particle behaves in the Earth's magnetic field if its adiabatic invariant is conserved. Fig. 1 shows the magnetic force lines of the Earth at not very large distances from it where the field is still not yet appreciably distorted by the solar wind. Also shown in this figure is the trajectory of charged particles moving along a force line from the plane of the equator to the pole. As the particle approaches the pole, it will move in an increasingly stronger field (the force lines clump together) and its directed velocity will decrease due to the continuously acting repulsive force. /7

For a specific magnetic field intensity, dependent only on $v_{\parallel} / v_{\perp}$, the particle will halt and then will begin to move in

the opposite direction. On attaining the domain of the strong field at the other pole, the particle will again be reflected. Moving between the strong field domains, the particle will be locked in, as in a trap. It is precisely in this manner that fast charge particles are held in the Earth's magnetosphere, forming the well-known radiation belt.

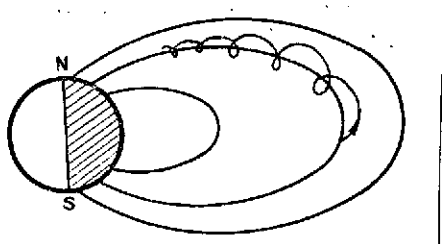


Fig. 1. Part of trajectory charged particle in Earth's magnetic field. As particle approaches pole, it will move in an increasingly stronger field. The energy of its rotational motion will rise, while the energy of its translational motion will decrease. For a specific magnetic field intensity a particle is reflected and begins moving in the opposite direction.

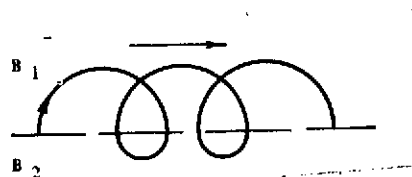


Fig. 2. Trajectory of motion of a particle across an inhomogeneous magnetic field. The dashed line indicates the boundary of the weak field B_1 and the strong field B_2 . The force lines are directed perpendicular to the plane of the drawing.

Now let us examine what an inhomogeneity in the magnetic field in the direction perpendicular to the force lines will lead to. In this case the particle will move along a complex trajectory, drifting in a direction perpendicular to both the force lines as well as to the magnetic field gradient. The drift motion is clear from Fig. 2. The force lines of the magnetic field are perpendicular to the plane of the drawing. Instead of a smooth variation in the field, the figure shows an idealized picture with an abrupt boundary (dashed line) between the weak B_1 and strong B_2 magnetic fields. In the weak magnetic field the charged particle will move along a circle having a larger radius. On crossing the boundary, it enters the strong field. Here the radius of curvature of the particle trajectory is small. By successively crossing the boundary of fields B_1 and B_2 and moving part of the time in the strong field, and part of the time in the weak field the particle drifts along the boundary. If instead of a sharp boundary there is a gradual increase in the field, the radius of curvature of the trajectory will vary smoothly, but the

pattern of drift motion will remain the same. The intensity of the Earth's magnetic field decreases with increase in distance, therefore particles drift along its magnetic axis. Drift in an inhomogeneous field is superimposed on the vibrational motion of the particle being reflected from the strong field domains.

The force acting on a charged particle in a magnetic field depends on the particle charge; therefore, positive and negative particles drift in different directions. The different drift direction in general can lead to changes in the distribution of charges and, thus, to the appearance of an electric field. The drift of electrons and positively charged ions along the Earth's magnetic axis does not lead to the separation of charges. All charges, simultaneously rotate about the axis. Electrons rotate toward one side and ions -- toward the other, and nowhere is an excess of charges of the same sign formed. Thus, the legitimacy of using the single-particle approximation in analyzing the behavior of particles in radiation belts is self-evident.

Polarization effects clearly show up in a confined plasma bunch placed in an inhomogeneous magnetic field. By drifting in different directions, electrons and ions accumulate at the opposite boundaries of the plasma. As charges build up, the electric field grows stronger and begins to influence the electron and ion trajectories. Further particle motion occurs in a self-consistent field, and the single-particle approximation becomes inappropriate. However, even for this case we can qualitatively predict the behavior of the bunch. By tracing the particle trajectories, it is not difficult to see that the direction of the polarization electric field is such that the drift in "crossed" electric and magnetic fields leads to ions and electrons moving in the direction of the weak field. A more rigorous inspection shows that the plasma bunch behaves like a diamagnetic material and is repelled from the domain of the strong magnetic fields.

If the plasma is simultaneously in a magnetic and in an electric field whose force lines are perpendicular to each other, drift develops in the direction perpendicular to the force lines of both fields. Particles drift at the velocity $v_D = cE/B$. The pattern of drift trajectories for this case is shown in Fig. 3. The force lines of the magnetic field are directed perpendicular to the plane of the drawing. A remarkable feature of drift in crossed electric and magnetic fields is the fact that drift velocity does not depend on particle charge and mass. The entire plasma, as a single entity, will move at the velocity v_D and no charge separation will occur.

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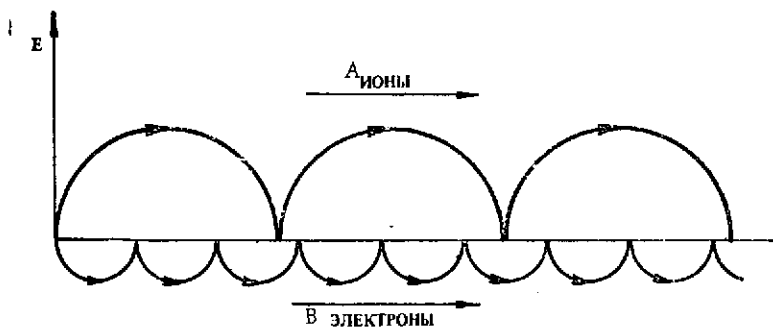


Fig. 3. Motion of ion and electron in cross magnetic and electric fields. The magnetic field is directed perpendicular to the plane of the drawing. The electrons and ions drift in one direction and at the same velocity.

KEY: A. Ions
B. Electrons

When we look at different effects in the Earth's magnetic sphere it is usually maintained that the force lines of the electric field are perpendicular to those of the magnetic field. The component parallel to the magnetic field cannot be large, since the free displacement of charges along the magnetic field force lines leads to the rapid equalizing of the potential along the force line. For a long time the equipotentiality of the magnetic force lines (that is, when the entire force line is at

the same potential) was assumed to be unquestioned in geophysics. In recent years it was shown that specific plasmonic processes interfere with the rapid equalizing of potential at times, but even these processes cannot, evidently, promote the appearance of large potential differences along a force line.

Barium Clouds

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Among the few active experiments that have been conducted in the Earth's magnetosphere thus far, the so-called barium clouds have been the most widespread. The idea of the experiment is to produce in the magnetosphere a bunch of rarefied plasma and to observe its evolution from the glow of the ions. If the plasma bunch has a low concentration and therefore its gas-kinetic pressure is much lower than the magnetic pressure, the magnetic field of the magnetosphere does not suffer appreciable distortions. The behavior of charged particles in the plasma is determined by two main processes: by diffusion and by drift in the electric and magnetic fields. If the plasma temperature is low, the drift velocity in a nonuniform magnetic field need not be taken into account since it is small compared to the drift velocity in crossed magnetic and electric fields. This derives from the proportionality of the drift velocity in a nonuniform magnetic field to the particle energy. When the electron energy is ~ 1 eV, which roughly corresponds to the mean energy in a plasma at a

temperature $\sim 10,000^\circ$, the velocity of this drift at low altitudes is 0.1 cm/sec. The plasma temperature in barium clouds usually does not reach $10,000^\circ$.

The electric field in a magnetosphere, as indicated earlier, must have a well-pronounced anisotropy. The joint action of the electric and magnetic fields oriented perpendicular to each other causes the charged particles to drift in a direction perpendicular both to $\mathbf{E}$ and $\mathbf{B}$. The velocity of the electric drift of all particles depends only on the intensities of the electric and the magnetic fields.

So we note that electron and ion transport velocities due to the electric drift can differ owing to collisions with neutral atoms, since the frequency of electrons and ions colliding with atoms is not the same. The difference in the velocities of particles with different charges means the appearance of an electric current perpendicular to $\mathbf{E}$ and $\mathbf{B}$. This is the so-called /11 Hall current. Under steady-state conditions and in the absence of neutral atoms, the Hall current is absent. If the barium cloud of a plasma is formed far enough from the Earth's surface, collisions with neutral atoms are extremely infrequent and do not influence cloud dynamics.

If the intensity of the magnetic field is known, then by observing the displacement of the plasma cloud due to the electric drift, one can determine the radial component of the electric field. The displacements of the plasma bunch are most conveniently studied against the background of a glowing cloud of neutral gas, on which electromagnetic forces have no effect.

The perpendicular field component in this experiment cannot be measured, since it is impossible to directly observe the displacement of the plasma cloud along the line of sight. For this purpose, in principle, the Doppler shift of spectral lines proportional to the radial velocity is suitable, but in actually existing electric fields this displacement is too small and the Doppler effect is not used in experiments with barium clouds.

If the displacement of the plasma cloud as a whole permits measuring the electric field in the magnetosphere, observing cloud deformation makes it possible to determine the direction of the magnetic force fields. The anisotropy of the plasma diffusion leads to the well-defined stretching of the plasma cloud along the force lines of the magnetic field. At low concentrations, when collisions between particles are extremely rare, the flight of the plasma along the magnetic field occurs at particle thermal velocities. The polarization electric field arising due to the fact that the thermal velocity of electrons is higher than the thermal velocity of ions is the only factor

preventing the independent motion of ions and electrons along force lines, and that the boundary of the plasma cloud an electric field is formed, accelerating ions and retarding electrons. However, at not very high electron temperatures this effect does not make a significant contribution to ion acceleration and it can be assumed that the expansion of the plasma along the field is determined mainly by the ion thermal velocity.

As for the velocity of plasma expansion perpendicular to the magnetic field force lines, here the situation is substantially different. Expansion of a rarefied plasma in this case does not occur without collisions, and allowing for collisions leads to quite a low diffusion coefficient. An isolated collision can displace a particle across a field by not more than one Larmor radius and it takes on a kind of role of the mean-free path length across the field. Calculations show that the diffusion coefficient of a plasma across a field is inversely proportional to the square of the magnetic field intensity and to the square root of temperature. The abrupt anisotropy of the distribution of diffusion coefficient leads to stretching of the plasma bunch along the fields and it rapidly takes on a spindle-like form, which enables one to determine the direction of the force lines. /12

It is most natural to produce a plasma cloud by evaporating in space cesium or lithium, that is, elements with a low ionization potential. Then due to the photoionization by solar radiation, cesium or lithium ions are formed, and observing these then permits one to measure the electric field of the magnetosphere. A more detailed consideration shows us that lithium and cesium are poorly suited for these experiments. The brightest spectral lines of ions of alkali metals lie in the far ultraviolet region and are inaccessible to observations from Earth owing to intense absorption of the radiation in this spectral range in the atmosphere. But using special methods of observation of the type of radiofrequency probes makes the experiment too cumbersome, which casts doubt on the soundness of the enterprise.

Barium proved to be most suited for experiments with plasma clouds. Having a much higher ionization potential (5.21 eV) than cesium (3.89 eV), nonetheless it is ionized much faster by solar radiation. The reason for this is the existence of a very low metastable excitation level, owing to which ionization can occur in a stepwise manner, by successive absorption of two quanta belonging to the visible spectral region. When the first quantum is absorbed, the electron passes to the excited level, and upon absorption of the second quantum, the electron escapes from the atom. The mean ionization time of barium is 19 sec; it is 1000 sec for cesium. /13

The resonant line of neutral barium $\lambda = 5535 \text{ \AA}$ lies in the visible spectral region and is readily observed. Finally (and this is the main advantage), a singly-ionized barium ion has a bright resonant line $4554 \text{ \AA}$ also lying in the visible spectral region. The latter is readily excited by the resonant absorption of solar radiation and its intensity proved to be fantastically high. It suffices to state that when an ordinary camera is used each barium ion excited by the continuous solar spectrum sends roughly one quantum a second per each cm^2 of photographic film surface. True, the light flux of ionized barium proves to be about one order of magnitude lower owing to the presence in the continuous spectrum of an absorption line (Fraunhofer line) also belonging to ionized barium. But in spite of the presence of the Fraunhofer line, the radiation flux still proves to be so intense that in an exposure of 1 sec with an ordinary camera one can photograph a barium cloud in which there are only 10^9 ions per cm^2 .

Experiments with barium clouds must be conducted while the barium cloud is being lit by sunlight, however solar radiation scattered by the air molecules does not enter the camera objective lens. These conditions arise soon after the Sun sets or before its rise.

To form a cloud of neutral barium, which is then ionized by solar radiation, an explosive mixture of copper oxide and barium is used. The barium charge is usually injected at a given point in space with a rocket and there exploded. The main measurements of the electric fields using a barium plasma were carried out at an altitude of several hundreds of kilometers. The number of individual measurements conducted at different places is so large that even now attempts are being made at compiling a map of the electric field. Typical values of the component of the electric field perpendicular to the force lines of the Earth's magnetic field is $(1-3) \cdot 10^{-5} \text{ V/cm}$. In the polar light zone the electric fields are greater by roughly one order of magnitude. To get an idea of the scale of the barium cloud drift velocities measured, we note that at a magnetic field intensity of 0.1Γ and an electric field intensity of 10^{-4} V/cm , the barium cloud velocity is 1 km/sec.

/14

Experiments With High-Concentration Plasma Bunches

The possibility of using barium clouds is not limited to measurements of electric fields in the magnetosphere and determining the direction of magnetic force lines. When measuring electric fields, it is necessary to work with a barium plasma not introducing substantial distortions in to the natural state of the electric and magnetic fields. This is achieved by using quite

rarefied plasma. The thermal energy of barium plasma enclosed per unit volume must be much smaller than the energy density of the magnetic field and the density of the thermal energy of the plasma of the magnetospheric plasma. Of course, the concentration of the barium plasma cannot be very small either. Otherwise, the intensity of its glow would be too weak for observations or photography.

The behavior of the barium cloud becomes substantially different if the same barium charge that is used in measurements of electric fields is exploded at altitudes of several tens of thousands of kilometers from the Earth's surface. Since the Earth's magnetic field falls off in this range distances roughly inversely proportional to the cube of distance, the density of the magnetic field energy (we recall that it is proportional to the square of the magnetic field intensity -- $B^2/8\pi$) at large distances usually becomes smaller than the density of the barium cloud thermal energy. The barium experiment at these altitudes takes on an entirely new content and an active, even though limited in scale, influence on the magnetosphere.

In a chart experiment of NASA (US) and the Max Planck Institute (FRG), a charge of a mixture of barium and copper oxide weighing 10 kg was exploded at 31,500 km. The charge was carried on a Scout rocket over the American continent near the equator. The experiment was preceded by careful measurements of the state of the magnetosphere and observations of the Earth's cloud cover. Results of these measurements made it possible to select the suitable time for the experiment. Even a slight cloud cover could interfere with taking clear photographs and the study of magnetic perturbations introduced by the barium plasma required the quiet state of the magnetosphere. The magnetic activity before the rocket launch and during the entire experiment was low. /15

The stations for visual observation and photography of the barium cloud were in the southern part of the United States, in Chile, and in Peru. A specially prepared aircraft expedition operated along the east coast of America. A network of photographic equipment strung out over a thousand kilometers, and operating synchronously, made it possible to photograph with high precision the spatial evolution of the barium cloud.

The location of the experiment was selected so that the force line of the magnetic field passing over the presupposed blast point of the charge intersected the Earth's surface in the area of the Canadian geophysical observatory at Great Whale. The preciseness of the rocket launch and its control ensured that this force field would pass within 100 km of the observatory. Observatory instruments were able to record the perturbations of the

magnetic field propagating along the force lines. Photographic equipment was ready to photograph the glow of the upper atmospheric layers due to fast particles from the Earth's radiation belt being precipitated along the force line. The possible effect of artificial plasma formations on the behavior of fast particles forming the Earth's radiation belt at the present time is being intensively studied by theoretical scientists. Experiments on this problem are outlined in Section 6.

The tracking stations were equipped with photographic recording equipment with a focal length of 350 mm and an aperture of 1:1. A television camera with electron-optical amplifier, equipped with a light filter singling out the spectral line 4554 Å was specially developed. This camera could resolve details 6 km in size at a distance of 31,500 km. The exposure time was 0.5 sec or 0.03 sec. Also used was a scanning photo-electric device successively measuring the glow intensity of the sky at different points. At a radiation flux of $3 \cdot 10^4$ quanta per second per square centimeter, the output signal was 1 V. All these technical details are cited in order for the reader to grasp an idea of the scale of the preparatory work preceding the experiment. The length of the experiment itself was measured in minutes. The experiment was controlled by means of a technological artificial Earth satellite, which all the observation stations were in direct sight of, as well as monitoring and control devices. /16

After the barium charge had been exploded, a spherically symmetric expansion of the cloud of blast products was observed for several seconds. Here the cloud's center of gravity continued to move at the velocity of the fourth stage of the rocket on which the barium charge had been placed before the blast. During this phase the main contribution to the glow came from the lines of neutral barium and strontium atoms. Strontium was contained as an impurity in barium, and its bright resonant line 4607 Å made it possible to conduct observations of the neutral gas after all of the barium had entered the ionized state. The glow front of the neutral gas had a velocity of 1.2 km/sec.

With increasing travel, the glow of the neutral atoms diminished and simultaneously the brightness of radiation from the spectral line 4554 Å belonging to the Ba^+ ion rose. This meant that the neutral barium had ionized and a cloud of barium plasma had formed. In color photographs it was distinctly clear that the expansion of the ionized barium occurred at the same velocity as the neutral barium, only along the directions of the force lines. Across the force lines the expansion of the barium plasma was retarded. Further expansion of the barium plasma along the force lines occurred even faster than the expansion of the neutral gas. The authors of the experiment accounted for this

by the additional energy that the electrons obtained during photo- /17
ionization. Since the polarization electric fields prevented the
flight of fast electrons, the ions were accelerated in these fields,
receiving energy from the electrons. Fig. 4 shows the photograph
obtained 2 minutes after the charge had been exploded. Already
here we can see the weakly noticeable spherically symmetric glow
of the neutral gas (mainly cesium vapor, since barium had already
entered the ionized state) and against its background can be seen
the bright spindle-like glow of ionized barium. In this photo-
graph the force lines of the magnetic field are directed roughly
at an angle of 45° to the vertical, that is, the barium plasma
cloud was elongated along the magnetic field.

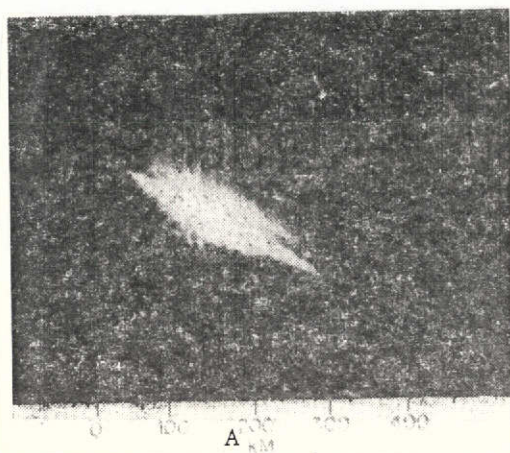


Fig. 4. Photograph of
barium cloud at high
concentration 2 min
after the explosion
of the charge. The
plasma was spindle-
like in shape, elon-
gated along a force
line. Above can be
seen the separating
layer of the plasma.
Around the plasma glows
neutral strontium.
KEY: A. km

The effect of the barium plasma
reacting with the magnetic field was
clearly recorded with a magnetometer
placed on the same rocket that lifted
the barium charge. These measurements /18
showed that the formation of the
ionized barium cloud was accompanied
by a significant weakening of the
magnetic field intensity at the point
where the cloud was formed. The
observed effect is analogous to the
skin effect well known in electrical
engineering. The rapidly growing
magnetic field does not immediately
penetrate within massive metal objects.
The increase in the magnetic field
intensity leads to the appearance in
the conducting bodies of surface currents.
The fields of induced currents, super-
imposed on the external field, produces
a zero intensity within an ideal con-
ductor. In actual conductors, due to
Joule losses in current heating, the
induced currents die off, and the
field penetrates within according to
an exponential time law.

In a magnetic field, the formation
of a plasma with sufficiently high
conductivity also leads to the appearance
of induction currents displacing the
magnetic field from the region occupied
by the plasma. The plasma enlarges

across the magnetic field until, as the result of the expansion,
its gas-kinetic pressure drops to the pressure of the magnetic
field. Further evolution of the plasma cloud is associated with
the streaming of the plasma bunch along the magnetic field and

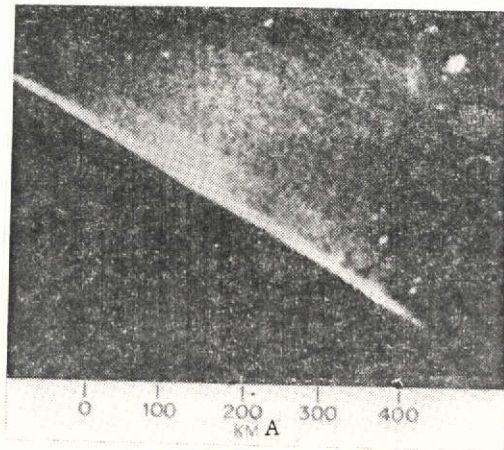


Fig. 5. Below is the glow of the main barium cloud elongated along a force line. Above can be seen layers separating from the cloud; they formed at different moments of time. The photograph was taken 9 min after the cloud had formed.
KEY: A. km

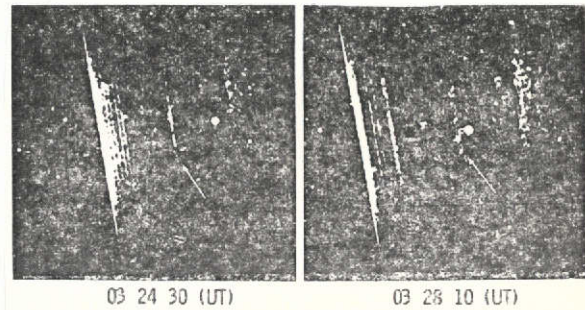


Fig. 6. Photographs of high-concentration barium clouds 20 and 23 minutes after formation. Layers separating from the main part of the cloud can readily be seen. All the layers were elongated along force lines. The inclination of the force line in this figure differs from the inclination in Figs. 4 and 5 since the photograph was taken from another tracking station.

simultaneously with the dying out of the induced currents, therefore, /18 the gradual mutual diffusion of the magnetic field and the barium plasma. The characteristic "mixing" time of field and plasma is proportional to the electrical conductivity of the plasma and the square of the cloud dimension.

Since the rocket velocity during the period of barium cloud formation is small, it can be assumed that the measurements pertain to a specific point within the barium clouds. An interesting aspect of the magnetic measurements is the short-lived abrupt rise in the magnetic field intensity following the attenuation caused by its displacement produced by the plasma. Data available to the experimenters were inadequate to uniquely account for this field impulse. It is most natural to assume that on attaining the state of equilibrium between field and plasma, the cloud boundary executes damping vibrations about the equilibrium position. Then the oscillating boundary can intersect the cloud one or more times, and each passage of the rocket beyond the bounds of the cloud must cause an impulse of the magnetic field in the magnetometer readings. The number of impulses depends on the number of oscillations and the position of the rocket. If everything favors this, in this case the rocket passes the plasma boundary

once before the currents in the plasma can die off. Thus, it can be assumed as proven that deformation of the barium cloud is accompanied by an intense magnetic perturbation if the amount of vaporized barium is large enough.

The layering of the plasma was a new unexpected physical result. The layers lay along the force lines of the magnetic field. They were observed on one side of the main barium cloud. The layers travel relative to the cloud in the easterly direction (in the direction the Earth rotates) at first at an acceleration, and then they take on the same limiting velocity. Photographs of the layers taken 9 and 23 minutes after cloud formation are shown in Figs. 5 and 6, respectively. To the left can be seen the brighter main cloud of barium plasma and to the right of it above can be distinguished the layers. The photographs were taken from different observation stations. By comparing the photographs one can see the evolution of the pattern. The layers close to the main cloud had not yet acquired their final velocity and were not able to markedly separate in 14 minutes, while the further removed layers were able to move much farther toward the east.

Thus far there is no complete theoretical interpretation of this phenomenon. Evidently, layering of the cloud is a consequence of the hydrodynamic instability of the plasma. This instability arises when the intensity of the magnetic field surrounding the plasma falls off with increasing distance from the boundary of the plasma. The mechanism of buildup of instability can be represented as follows. If at the equilibrium boundary where the plasma pressure is equal to the magnetic pressure a perturbation arises and along the boundary section the plasma penetrates the field, the penetrating plasma now encounters the lesser pressure of the magnetic field and it breaks through the boundary. The instability of the plasma boundary and the magnetic field is analogous to the well-known instability of the boundary of a heavy liquid at the surface of a light liquid. It is called the /21 Rayleigh-Taylor instability.

The barium plasma layers parting from the main area then take on the velocity of the "enveloping" magnetospheric plasma, that is, their velocity is determined by the drift in the electric and magnetic fields. The intensity of the electric field at the equator at an altitude of 31,500 km determined in these experiments was found to be 0.46 mV/m.

Not all the data obtained in the experiments have been processed at the present time, and many questions are still unclear. For example, the mechanism of layer acceleration is unclear. The acceleration time evidently depends not only on the mass of the layers, but also on the layer dimensions, that is, it is determined by the time required to restore the initial intensity of the electric field at a given point.

Plasma Fluxes in the Magnetosphere

Much scientific interest is drawn to experiments with accelerated bunches of barium plasma. These experiments are important not only to the study of near-Earth space, but also for further progress in plasma physics, since space itself can be used as a giant installation exhibiting a number of advantages over laboratory devices.

Recently an experiment with a plasma jet directed along a force line of the magnetosphere was conducted in the United States. Explosion-type sources reminiscent of antitank-shaped charges were used for this purpose. The scheme of the shaped plasma source is shown in Fig. 7. A conical cavity was formed in a cylindrical block with a 25 kg primer; the surface of the cavity was coated with a 0.5 cm thick layer of metallic barium. The total amount of the barium was 880 g. With the properly positioned igniter, the detonation wave in the primer propagated so that the blast products were rejected along the cone axis.

The rocket brought the shaped source to an altitude of 467 km./22 At the moment of triggering of the detonator, the source axis coincided with the direction of a force line of the Earth's magnetic field to a precision of 3° .

Two successful attempts to trace the plasma flux along the forced line $L = 1.25$ were carried out over the Hawaiian Islands in October 1971 (here L is the distance of the force line from the Earth's center in the plane of the equator, expressed in Earth radii).

The glow was observed along the entire force line (6900 km) and was photographed from ground stations as well as from aircraft with electron-optical equipment. The glow front reached the southern hemisphere at a mean velocity of 13.5 km/sec. Before reaching the southern conjugate point, the diameter of the glowing jet was 3 km, and the concentration of the barium ions was $10^3 - 10^4 \text{ cm}^{-3}$. The glowing barium jet traveled nearly exactly along the magnetic force line, enabling its shape to be observed from the Earth and to be photographed.

The values of the electric field determined simultaneously at the conjugate points were the main measured quantities in these two experiments. The data proved unexpected to the geophysicists. Both the magnitude of the drift velocity as well as its direction were found to differ in the northern and southern hemispheres. In the northern hemisphere the electric field intensity was found to be 10^{-5} V/cm , and $7 \cdot 10^{-6} \text{ V/cm}$ in the southern hemisphere. Evidently these data must cast doubt on the concept of the equipotentiality of the magnetosphere force /23

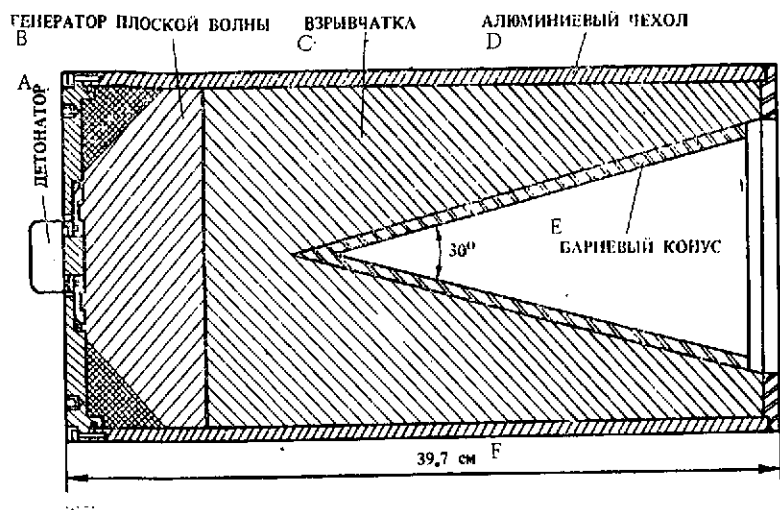


Fig. 7. Scheme of shaped charge for producing a barium jet in the magnetosphere. Before triggering of the charge, the cone axis was positioned along a force line

KEY: A. Detonator
B. Plane wave generator
C. Primer
D. Aluminum casing
E. Barium cone
F. cm

lines. In these experiments information on the shape of the force line was obtained. An exact knowledge of the shape of the force line permits arranging the recording instruments in the vicinity of the conjugate point when probing is being carried out with beams of fast electrons. One more experiment in which a shaped barium jet was oriented along a force line was conducted in March 1972 in Alaska at an altitude of 500 km. The barium jet was the least at the force line $L = 6$, that is, it had to pass over the equator at a distance of five Earth radii from the Earth's surface. However, on attaining the altitude of $3 R_E$ $\sqrt{E} = \text{Earth}$ in

17 min, the image was degraded due to a

developing strong substorm. Magnetic field fluctuations proved to be so rapid and sizable that the plasma flux was not able to be tracked from the changing shape of the force line, became dissipated, and then was not observed.

The shaped methods of producing plasma fluxes in the magnetosphere have two main disadvantages. First of all, it is impossible to repeat the experiment and to verify its results. Secondly, the "controllability" of the experiment is limited since there is no possibility of varying within significant limits a parameter as important as the velocity of the plasma flux.

The range of possibilities of experiments in the magnetosphere is much broadened if one uses plasma accelerators. Plasma accelerators began to be developed in relation to the problem of controlled thermonuclear reactions and today they are widely used in various laboratory experiments. At the present time there are several types of plasma accelerators, and nearly all are based on the reaction of electromagnetic fields with plasma. The most sizable plasma concentrations in a flux come from use of the electrodynamic accelerator in which a plasma bunch is

repelled by magnetic pressure. The magnetic field exerts a pressure of $B^2/8\pi$ on the plasma. Depending on the magnitude of the magnetic field, the plasma bunch acquires different velocities.

The electrodynamic plasma accelerator was first developed in the laboratory of L. A. Artsimovich as early as 1956 and today the problem can be reduced to building a model suitable for use on satellites and rockets and capable of producing the plasma of singly-ionized barium. In a paper by L. V. Leskov, V. V. Savichev, and their coworkers given at the 11th All-Union Conference on Plasma Accelerators, it was reported that such a model has already been built.

A pulsed electromagnetic plasma accelerator can solve several problems of plasma-magnetic field interaction that thus far have not yet been solved in laboratory conditions. The role of a giant laboratory will be assigned in these experiments to near-Earth space.

Laboratory experiments on the interaction of plasma fluxes with a magnetic field were begun as early as 1960, but many aspects of the dynamics of a plasma bunch remain unclear. Thus far it is impossible to describe even the pattern of motion of a bunch in a transverse magnetic field. Theory usually can explain experimental facts, but often it is unable to predict the behavior of a bunch in specific conditions. Before proceeding to examining experiments in the magnetosphere, as an illustration of the statement made here, we can look at a curious example of the behavior of plasma in the laboratory.

In the laboratory experiments of Lindsberg and Christofferson, a study was made of a plasma jet in a magnetic field that had a section of rectilinear force lines and a section of curved lines (Fig. 8). The plasma was injected (introduced) along the rectilinear force lines from left to right; the mean free path length exceeded the dimensions of the device. It is most natural to assume that the plasma flux along the rectilinear section will travel along the force lines. The experiments showed that this assumption and the pattern of motion proved to be much more complex. /25

Only the bow part of the jet will move along the rectilinear force lines. When the plasma jet enters the curved field, polarization occurs, but owing to the high plasma conductivity along the field the potential of the entire line changes, including the rectilinear section. As a result, the polarization electric field perpendicular to the plane of the drawing is induced here also in the rectilinear section. Drift in the "crossed" fields leads to the displacement of the jet upwards, as is schematically shown in Fig. 8.



Fig. 8. Scheme of motion of plasma jet in curved magnetic field. The jet is deflected from the rectilinear section of the field due to polarization in the area of the curved lines.

KEY: A. Plasma jet
B. Magnetic force lines

Numerous examples of the unexpected behavior of plasma can be cited. Conditions at the walls of the vacuum chamber had a particularly strong effect on plasma behavior in laboratory devices. In particular, the escape velocity of charges accumulated along a force line depend on wall conductivity. Formation of nonconducting films on metal walls and increase in surface conductivity of walls made of a dielectric in the presence of plasma radiation does not permit recording of quantitative data on the trajectory of a bunch in a magnetic field in the laboratory. The Earth's magnetosphere in this sense is an ideal laboratory with controllable initial conditions.

A pulsed electrodynamic accelerator can produce a barium plasma bunch with parameters such that its behavior in the magnetosphere can be observed from a spacecraft on which the accelerator /26 is installed, or from another spacecraft nearby. Let us look at the behavior of a bunch with a mean velocity of $5 \cdot 10^6$ cm/sec and a population of singly ionized barium ions $N = 10^{18}$. Generation of this bunch can be achieved in a plasma accelerator weighing no more than 20 kg, which is quite suitable for an onboard instrument.

The plasma bunch injected into the magnetosphere expands with a thermal velocity until its gas-kinetic pressure is not equalized by the magnetic pressure. Subsequently, the unimpeded expansion will occur only along force lines. At a mean energy of random motion of 20 eV, the equilibrium of pressures will set in when the size of a cloud becomes equal to ~ 20 m. During the attainment of equilibrium, the concentration will be $4 \cdot 10^7$ cm $^{-3}$, and the ion population per unit cloud surface will be about 10^{11} cm $^{-2}$. This surface density makes it possible to take photographs with a high-speed motion-picture camera with a frame exposure time of 10^{-2} sec. Using an electron-optical converter, one can take photographs with an exposure that is two orders less. The intensity of the radiation from the barium atoms in the plasma moving toward the Sun or from it can be several times greater than from a still cloud. This is due to the Doppler shift in the wavelength, which brings the absorption line beyond the bound of the solar-radiation Fraunhofer line. Since the expansion time is $\sim 10^{-3}$ sec, an electron-optical converter can provide quite detailed information on the stage of free expansion.

During the entire stage of free expansion, the magnetic field cannot have a strong influence on the motion of the bunch injected across force lines. The bunch with high electrical conductivity freely pushes apart the force lines and the dissipation of its energy is associated only with the currents induced by changes in the magnetic field.

Simultaneously with the expansion of the bunch the field penetrates into the plasma. Calculating the rate of diffusion of the magnetic field into the bunch requires that we know the changes in the electron temperature during the expansion and also the effect of specific plasma processes on conductivity. Gross estimates of the diffusion time of the magnetic field give a value commensurable with the expansion time until the balance of pressures has been attained. For the next stage of bunch dynamics a model in which the plasma will move in "crossed" fields is most appropriate: the magnetic field of the magnetosphere and the electric field induced by polarization. Initially, as long as the mean bunch charge is virtually equal to zero, the motion of the plasma as a whole continues to be rectilinear with its former velocity, and then in the limiting case of low concentration the ions will begin to move along circles with the Larmor radius independently of the electrons. /27

As soon as the magnetic field begins to impede the expansion of the bunch across the force lines, a further decrease in the concentration is slowed down and will occur nearly directly proportional to the expansion time. An increase in the volume of the bunch during this stage is due exclusively to the streaming of the plasma along the field. This stage is characterized by the unstable plasma state owing to pressure anisotropy. Pressure anisotropy is a consequence of the one-dimensional expansion. The component of the particle velocity across the field remains unchanged, but the component of the velocity of random motion along the field decreases adiabatically. Since collisions are unable to remove the pressure anisotropy, there is every reason to expect the development of kinetic instabilities.

At a high electron temperature, the bunch dynamics will be somewhat different. The equality of pressures $B^2/8\pi$ and nkT will be attained before the field penetrates into the plasma. The bunch will expand, as in the case of mixing of plasma and field, along the force lines, but here at the boundary parallel to the force lines the pressure balance will be continuously maintained. This means that after the stage of free bunch expansion there follows a stage of bunch compression by the magnetic field across the force lines. The motion of the plasma bunch with high conductivity in the magnetosphere was examined by I. A. Zhulin, V. I. Karpman, and R. Z. Sagdeyev. They calculated the mean free path length of this bunch, on the assumption that the bunch entrains the ambient plasma.

In actual conditions at an altitude of ~ 300 km, the retarding path length must be several kilometers. An experiment studying the dynamics of a bunch in the magnetosphere is most conveniently conducted from a spacecraft, since it is extremely difficult to obtain a sharp photograph of an object 10 m in size from the Earth if this object is at the altitude of ~ 300 km.

The scheme of bunch behavior described here is evidently only a gross approximation to the picture that will be observed in actuality. A theoretical examination of individual stages of bunch dynamics can introduce some refinements and, evidently, permit formulating additional requirements on the setup of the future experiment.

Probing the Magnetosphere With Charged-Particle Beams

Phenomena accompanying the injection of fast plasma bunches into the magnetosphere are quite complex and diverse, and this factor hampers a detailed analysis of the processes occurring during injection. The problem of probing the magnetosphere can be posed more clearly in experiments with electron and ion beams. Investigation of magnetic fields as well as a plasma in a magnetic field using beams of charged and neutral particles has already long been used in the laboratory. In recent years beams of fast electrons have begun to be used also in studying the magnetosphere. The low plasma concentration in the magnetosphere and the rapid decrease of the scattering cross section with energy when charged particles collide permits, to the first approximation, the interaction of accelerated electrons with the magnetosphere plasma to be neglected. For example, at a distance of 200 km from the Earth's surface, where the plasma concentration is $\sim 10^5$ cm⁻³, the mean-free path length of a 10 keV electron is $2 \cdot 10^{15}$ cm, that, 100 times greater than the distance to the Sun. This does not mean that the interaction of the electron beam with the magnetosphere plasma is absent altogether. Actually, the electron beam causes electrostatic and electromagnetic vibrations of the plasma. These vibrations, on interacting with the cold plasma of the magnetosphere, imparts the beam energy to it. /29

The slowing down of the electron beam in a plasma in these conditions when collisions are extremely rare has not infrequently been observed and investigated in the laboratory. However, the results of the laboratory investigations cannot always be directly extrapolated to space. In laboratory conditions, with the electron beam operating time of 10^{-6} sec and the electron velocity of $5 \cdot 10^9$ cm/sec, which corresponds to an energy of 10 keV, the beam length is 50 m, that is, deliberately exceeds the size of the experimental device. In space this beam occupies a small part

of the Earth's magnetosphere surrounded by an undisturbed plasma and the beam deceleration conditions can prove to be otherwise. In space the electron beam formed by a pulsed electron gun is like a needle penetrating the ambient plasma. The spatial confinement of the beam imposes its own specific features on the pumping of vibrations in the plasma. At the time the first experiments were set up in space there was a lack of clarity on this problem. If one considers that the deceleration of the electron beam in the interplanetary plasma due to specific plasma processes is slight, its behavior will be determined by the interaction with the magnetic field and by collisions.

Investigation of plasma processes leading to the deceleration of the electron beam is far from the only task that this experiment must face. Depending on the specific conditions, the results can promote a solution of various problems of the magnetosphere. Tracking the beam in the Earth's magnetic field above all will make it possible to ascertain the shape of the force line and thus to permit a selection among various magnetosphere models.

Often in the literature the possibility of the continuous transition of several magnetosphere force fields into the interplanetary magnetic field has been discussed. The overall force lines open up a direct approach for cosmic rays entering into the magnetosphere, and therefore their detection is one of the most important problems in geophysics. The existence of these lines can be detected in experiments with electron beams. The electron flight time along a force line enables its length to be determined. When electrons move along a force line they experience drift both due to the inhomogeneity of the magnetic field as well as due to the presence of the active fields. By measuring the drift velocity, one can measure the intensity of the electric field just as is done with barium clouds.

/30

Besides interaction with the magnetic field of the magnetosphere, also noteworthy are problems of electron beams penetrating into the Earth's upper atmospheric layers. Based on the discussion given in Section 1, it follows that an electron injected into the magnetosphere will move along the force line; here the total energy remains unchanged. The slow drift along the Earth's magnetic axis is superimposed on the motion along the force line. If the deceleration of the electron due to the interaction with the magnetosphere plasma is small, then by moving along a force line the electron will be reflected when the field is at a specific value and will begin to move in the opposite direction. However, it also may turn out that the "mirror" point will lie below the atmospheric boundary, and then by being scattered by air molecules electron can be reflected from the atmosphere without attaining the "mirror" point. In scattering, part of the electron energy is lost. Some of the electrons, on falling into the atmosphere, lose all of their energy there.

Processes occurring when an electron beam is introduced into the atmosphere do not differ in any way from processes occurring during displays of the polar lights. Electrons excite and ionize neutral particles, and this process is accompanied by radiation in different spectral regions. In other words, injecting fast electrons into the atmosphere must cause a glow that can be called an artificial display of polar lights. The main contribution to natural polar lights comes from electrons having energies of tens of kilo-electron-volts, therefore it is precisely these energies that are needed to reproduce the phenomena occurring during the polar lights.

The first experiment in which electrons were injected into the magnetosphere was carried out in January 1969 by several research centers in the United States under the supervision of W. N. Hess. The experiment was preceded by a theoretical analysis of the problem that could be solved by means of an electron beam. /31 Main attention in setting up the experiment was paid to verifying the possibility of the beam traversing large distances in the magnetosphere, since theoretical predictions were contradictory.

W. N. Hess' experiment was carried out on a Aerobee rocket, which reached an altitude of 270 km. The electron accelerator was directed downward. It injected along a force line a series of electron pulses 1 sec in duration. The maximum current reached 0.5 A, and the maximum energy -- 10 keV. During the preparation of the experiment, apprehension developed in that as a powerful electron beam was being injected the rocket could be charged to a potential close to the accelerating potential of the accelerator and thereupon the entrance of fast electrons into the magnetosphere could be halted. In this case the fast electrons exiting from the accelerator begin to be decelerated in the electric field close to the rocket. To compensate for the charge entrained by the electron beam, the rocket was provided with an aluminum foil about 300 m^2 in area. After the rocket left the dense atmospheric layers the shield was rotated perpendicular to the force lines and served as a collecting surface for the thermal electrons of the plasma. This electron flux was able to compensate for the charge of the fast beam electrons.

In spite of the fact that the rocket deviated somewhat from its design trajectory, television equipment recorded glowing trajectories of electron beams that could be considered as artificial radiative-type polar light. Four beams, about 100 m in diameter, were recorded simultaneously at two stations. The photographs made it possible to show, with simple geometric constructions, that the electron beam prior to its complete deceleration in the atmosphere reached a distance of $\sqrt{105}$ km from the Earth's surface, that is, it traveled a path of almost 200 km before completely stopping. Thus, it was shown for the

first time that the simplified one-dimensional model adopted in calculating the deceleration of a beam due to specific plasma processes is inapplicable to a beam of confined dimensions. In these experiments, the theoretical possibility of determining the makeup of the atmosphere at different altitudes from the radiation spectrum of a beam polar lights display was proven. /32

A complex of radar and radiometric measurements was also provided under the program, however this part of the program remained unperformed. The launch of the rocket coincided in time with the appearance of a meteorite shower and the radars were not able to distinguish the pulses reflected by the meteorites traces from the ionization of the atmosphere by the electron beam. Atmospheric disturbances associated with the arrival of a bad weather front interfered with radiometric measurements from the ground, and the measurements directly in space were not made, since the launch of the second rocket specifically designed for these measurements was aborted.

An experiment in which an electron beam was injected along a force line from the northern hemisphere into the southern hemisphere and in which electrons returning to the launch site of the rocket after being reflected in the southern hemisphere from the upper atmospheric layers were recorded was carried out on 13 August 1970 by the J. R. Winckler group. A total of 3000 electron pulses 16 msec in length with energy of about 45 keV were injected. The beam current was 0.07 A. Injection of the electrons occurred at an angle close to 90° with respect to the force line, that is, the energy of translational motion was considerably less than the energy of rotational motion. We recall that an electron, having a velocity equal to zero along a force line must be repelled by the field along the force line toward the side of weakening intensity. If this electron will be reflected by a field in the other hemisphere and will be returned back, it will be repeatedly reflected at the injection point. Thus, for an electron injected at an angle of 90° to a force line, the point of injection is simultaneously the "mirror" point. In actuality, the electron will be reflected not exactly at the injection point, since during its flight time the trajectory will be somewhat shifted owing to drift along the Earth's magnetic axis. Instruments recording electrons reflected and returning from the southern hemisphere (electron echo) were on the same rocket as electron gun.

The rocket trajectory was selected so that the drift of electrons in the Earth's magnetic field during the time of their motion toward the reflection point and back again would be compensated for. This was necessary to record the electron echo by the rocket instruments. In 0.6 sec after the pulse injection, a reflected flux of electrons approximately 0.05 sec in length was clearly recorded, that is, the length of the electron beam /33

was stretched out by no more than 3-4 times. No strong (in any case by 1.5-2 times) change in the electron energy after reflection was detected. In 0.6 sec more, a signal from the second reflection was recorded at the sensitivity limit of the equipment. The third reflection could not be detected once.

In these experiments reflection of electrons occurred not owing to the buildup of the magnetic field intensity along the force line, but owing to the scattering in the Earth's upper atmospheric layers. The point is that for electrons injected from a rocket at an angle of 90° to a force line, the "mirror" point in the Winckler experiment was in the southern hemisphere below the Earth's surface.

The main result of the experiment apparently is the direct proof that a force line located far enough from the Earth's surface is continuous and that there are no sizable energy losses when a beam traverses in the magnetosphere distances of tens of thousands of kilometers. Interesting data were obtained with radio-recording equipment located in the rocket nose cone. The instrumented compartment was fired off before the electron gun was switched on and was thereupon traced along a trajectory close to the main part of the rocket. Radiation excited by the electron beam in the frequency range 1-10 MHz was detected. Evidently, the upper spectrum frequencies are electron plasma vibrations, and the lowest frequencies are most naturally attributed to "whistlers" -- electron waves propagating in the plasma in the presence of a magnetic field. These waves are easily excited in the magnetosphere and are recorded by a direct-amplification radio receiver as a characteristic whistle, hence their name.

Further experiments using more advanced equipment will assist in establishing a relation between radiation in various frequency ranges and particular wave processes occurring in the magnetosphere plasma. A phenomenon detected in the experiment with the electron beam which was entirely unexpected was the so-called "black cloud" effect: signals of ultrashort-wave transmitters, when an electron beam was injected, proved to be severely attenuated. This effect has not yet been satisfactorily explained. Thus, it is at present difficult to state what role the "electron echo" experiment will play in science. What is more important, the rising level of understanding of processes in the magnetosphere or newly formulated problems?

/34

Among the drawbacks of the "electron echo" experiment must first be cited the absence of any measurements in the region at which the electron beam was reflected and the overly low position of the point at which the reflection of electrons by the magnetic field should have occurred. The latter circumstance prevented investigating magnetic reflection as such. These and other shortcomings will be eliminated in the joint Soviet-French experiment called Arax.

In 1975 it is planned to inject electron beams from a rocket that will be launched in the southern hemisphere from the Kergelen Island. The injection must be made at a longer force line than in the Winckler experiment. In the Arax experiment $L = 3.8$, while in the Winckler experiment $L = 2.5$. The force line linking Kergelen Island and the northern hemisphere passes through Arkhangel'skaya Oblast. Here the "mirror" point will lie higher than above the Kergelen Island, which must ensure magnetic reflection without appreciable atmospheric influence. It is planned to set up a complex network of scientific instrumentation in Arkhangel'skaya Oblast. The electron accelerator will emit beams of electrons with different parameters and the injection will be carried out at different angles. When injected at small angles to the force line, the electrons will not be reflected by the magnetic field and will return to the northern hemisphere in the upper atmospheric layers. Equipment synchronized with the operating program of the electron accelerator will be used to photograph the artificial polar light displays.

As preparation for the Arax program, in May 1973, under the supervision of R. Z. Sagdeyev, the Zarnitsa experiment was carried out. /35 The main preparatory work and coordination of the observational groups was carried out by a laboratory directed by I. A. Zhulin (Institute of Terrestrial Magnetism and Propagation of Radio Waves, USSR Academy of Sciences). The electron accelerator was sent by rocket to an altitude of ~ 160 km. The accelerator emitted electron pulses 1 sec in duration, with an interval also of ~ 1 sec. The electron current was 0.5 A, and electron energy was 10 keV. Using television equipment, the glow caused by the electron beams in the altitude range 100-160 km was photographed. The motion of a spatially confined glow elongated along the force line could be clearly seen. In this altitude range the atmospheric density is high enough to observe the glow during passage of the electrons. The radio emission caused by the electron beam at the frequency 44.5 MHz was pulsed in nature, which evidently is associated with the rotation of the rocket. Data on radio wave scattering were also obtained. At the present time experimental material collected during the 2 minutes of the rocket flight is being processed. The absence of special accessories compensating for the charge entrained by the electron beam is an important technical feature of the Zarnitsa experiment. It was shown that at altitudes of ~ 150 km charge compensation is provided for entirely by the metal skin of the rocket itself.

Thus far, only electrons were used for corpuscular probing of the magnetosphere. In several cases it is more convenient to work with ion beams. The interesting possibility of using ion beams with uncompensated bulk charge for exploring perturbations of the magnetosphere magnetic field was examined by A. I. Morozov and R. Z. Sagdeyev. Underlying the basis of this experiment was the constancy of the period of rotation along the Larmor circle

experienced by particles exhibiting the same mass. If from a given point in space K (Fig. 9) simultaneously a group of charged particles with mass m having different directions in the plane perpendicular to the magnetic field and with different velocities is injected perpendicular to the force lines, after the time $T = 2\pi mc/eB$ all the particles will again turn up at the point K. When velocity distribution is present along the field the particles will be focussed not at a point, but will be smeared out along the force line extending through point K. The particles will be distributed over the section $l_{\parallel} = v_{\parallel \max} T$, where $v_{\parallel \max}$ is the maximum velocity along the magnetic field. This pattern of motion occurs in a field that is homogeneous over the extent of the Larmor orbit, which is valid to high accuracy for the Earth's field when nonrelativistic particles are used. /36

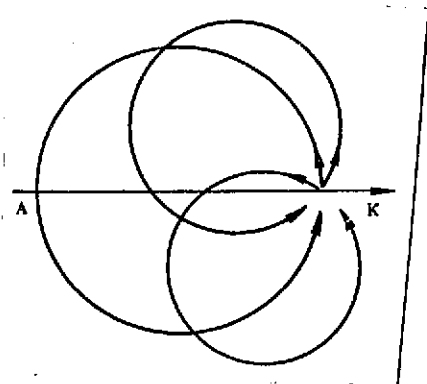


Fig. 9. Trajectories of ions injected into the magnetosphere across the field. Ions having the given mass, on exiting from point K, will return to it simultaneously, independently of the energy or direction of injection.

Let us now assume that the injection of particles at point K was carried out from onboard a spacecraft traveling along axis AK at the velocity v_0 , and then after the time interval T a "focus" of charged particles will be observed behind the craft at the distance $v_0 T$ to the rear of the craft. These foci will arise with a time interval T and a space interval $v_0 T$ in the craft-bound reference system. The intensity of the foci must gradually weaken due to smearing along the field. For injection at an angle to the force line differing from 90° , the foci will simultaneously move along the field.

When injection at an angle of 90° is used and the ship moves perpendicular to the field, the geometrical location of the foci will lie along the craft trajectory and can easily be recorded from a second spacecraft in a joint flight. The disturbance of this pattern will serve as an indicator of magnetic perturbations in the magnetosphere. To carry out this experiment, an electron beam is unsuitable since electrons at these energies have much greater velocities and a much smaller trajectory radius of curvature. As a result, in describing part of this circle in the magnetic field, an electron will strike the wall of the spacecraft, since the spacecraft will not be able to advance during this time any appreciable distance. /37

The range of possible uses of ion beams in the magnetosphere experiments evidently will continue to grow and many methods of corpuscular diagnostics of laboratory plasma will find application in space. For example, for many years now ion beams have been used in the laboratory to determine the spatial distribution of plasma potential. If an ion beam with specific energy is directed along a test plasma, its energy at a given point will change by the quantity $e\Delta\phi$, where e is the ion charge, and $\Delta\phi$ is the potential difference between the given point in space and the point of injection. Thus, by measuring the ion energy one can determine the potential of the point at which the energy is being measured. In the laboratory instrumentation severely distorts the distribution of the potential, therefore ordinarily it is not the energy of the particle that is measured, but the time of flight. In space, owing to the tremendous scale involved, one can measure directly the energy without introducing considerable distortions in the process.

The ion beam method can prove to be very useful in measuring the possible falloff of potential along the magnetosphere force line. For this purpose, one must use two spacecraft, simultaneously intersecting the same force line. On one of them a source of ions at a specified energy must be placed, and on the second -- a receiver and analyzer. Since the magnetosphere contains ions at different energies, onto the effect of measurement can be imposed a considerable background, therefore in the measurements ions whose content is low in the magnetosphere must be used. For example, deuterium or lithium. In this experimental setup, the equipment must include a device separating ions by mass.

Forced Precipitation of Particles From Radiation Belts

/38

The discovery of the Earth's radiation belt was the first scientific discovery made from artificial Earth satellites. It was found that a natural magnetic trap -- the Earth's magnetosphere -- is filled with fast particles, mainly electrons and protons. The reasons for the prolonged trapping of particles in the magnetosphere were examined in Section 1. The motion of each trapped charged particle can be represented as the superpositioning of three independent motions: a) rotation along a Larmor circle around a force line; b) motion along a force line with alternative reflection from the mirror points located in the different Earth hemispheres; and c) slow drift about the magnetic axis owing to the inhomogeneity of the magnetic field. The trapped particles will move along these complex trajectories and will fill a domain not differing strongly from a body of revolution with an axis coinciding with the Earth's magnetic axis. In shape, the radiation belt is closer to a doughnut than to a band. Sometimes one speaks of two radiation belts, the inner and the outer, one of which contains highly energetic electrons, and the other contains protons.

The radiation belt is continually being "built up" with new particles and simultaneously some of the particles are being lost, exiting along force lines into the Earth's atmosphere and causing displays of northern lights. The trapping mechanisms in the radiation belts are still not adequately studied. Evidently, the electron and ion trapping mechanisms differ. In any case, some of the radiation-belt protons are formed due to the radioactive decay of neutrons. These neutrons arise during nuclear reaction in the Earth's atmosphere caused by cosmic rays. The mechanism for filling with fast electrons will be discussed in the next section. Here we will be interested mainly in the mechanisms by which particles are lost from the radiation belt. It is important to note that the energy of particles trapped in the radiation belt is high. It is 10^{15} - 10^{16} J, comparable in order of magnitude to the energy released during a nuclear explosion.

/39

Naturally, scientists cannot be indifferent to this store of energy. Although essentially there are no specific ideas on how to make practical use of this energy, nowadays an experiment in which an attempt will be made to control the exiting of particles from the radiation belt is under discussion. Let us dwell more closely on the mechanisms by which particles leave the radiation belt. When a trapped particle leaves the radiation belt, its velocity vector must change its direction so that the energy of longitudinal motion will increase at the expense of a decrease in rotational energy. Then the mirror point for this particle will shift into the domain of a stronger field, and for a specific angle between the force line and the velocity vector, the particle will enter the Earth's atmosphere. This means that particles trapped by the magnetic field have an explicit anisotropy of velocity distribution. Among the particles trapped by the Earth's magnetic field there are no particles whose velocity vector forms with the force line an angle that is smaller than some critical value α_0 at which the particle is reflected back to its entry into the dense atmospheric layers. It is said of these particles that they are beyond the limits of the "loss cone" defined by the angle α_0 .

In order for a particle trapped by the magnetic field to be able to exit along the force line, its velocity vector must be brought within the loss cone. The angular distribution with "truncated" loss cone is not a thermodynamically nonequilibrium distribution. Particles trapped by the magnetic field resemble atoms long-lived in an excited state (so-called metastable state), which when subjected to an external influence pass into the ground state, giving off energy. The forced luminescence of metastable atoms makes it possible to obtain controlled light-energy fluxes in lasers. On analogy, the entire magnetosphere with its radiation belts can be represented as a gigantic

instrument of the laser type, whose triggering requires selection of the appropriate starting mechanism. The energy stored in this instrument is 10^{15} - 10^{16} erg.

Leakage of particles and the radiation belt must occur continuously by means of particle collisions between each other. /40
The collisions change the velocity directions and move the particles into the loss cone. This role played by collisions derives from the most general considerations. Collisions always bring a system closer to thermodynamic equilibrium and in particular they eliminate the anisotropy of angular distribution.

At high particle energies and low concentrations characteristic of radiation belts, collisions are so rare that their contribution to particle leakage is slight. Study of the departure of particles from the magnetic trap is extremely essential not only from the standpoint of space science. The rate of escape is a decisive factor in the fate of the end-purpose of thermonuclear research based on the prolonged trapping of the hot plasma in adiabatic traps.

Laboratory studies have repeatedly shown that the escape of particles from a magnetic trap is impossible to account for just by collisions. The existence of a specific plasma process leading to escape is indicated by pulses of electromagnetic radiation accompanying anomalously rapid particle losses along force lines.

A theoretical analysis made in the laboratory of L. A. Artsimovich by the then junior theoreticians R. Z. Sagdeyev and V. D. Shafranov showed that the anomalous escape of particles can cause resonance interaction of waves in a plasma and individual particles. Without delving into the theory of this phenomenon, let us look at the gross physical picture that enables us to understand the meaning of resonance interaction. If an electromagnetic perturbation propagates along a force line, then generally speaking its effect on individual particles is small. The influence becomes appreciable if the phase wave velocity is close to the particle velocity along the force line. In this case the particle "senses" the field of the wave for a long time in a fixed phase. For a long time a nearly constant force acts on the particle, rotating the velocity vector (that is, the results of this interaction essentially differs not at all from a collision). The velocity vector can enter the lost cone and the particle will escape from the magnetic trap. But if the particle velocity is small compared with the velocity of the wave, the interaction takes on the nature of weak oscillations; the adiabatic invariant remains virtually unchanged /41 and the particle remains for a long time trapped by the magnetic field.

"Whistlers" can be waves bringing resonant particles into the lost cone. The instability of "whistlers" develops when the anisotropy of the distribution of particle velocity vectors is quite large. The anisotropy coefficient must exceed the ratio of the frequency of the wave to the frequency of rotation of the electron in the magnetic field. The critical energy of precipitation, that is, the energy at which the electron velocity coincides with the phase velocity of the wave depends on the anisotropy coefficient and is inversely proportional to the concentration of particles in the radiation belt. The critical energy is 30-40 keV for the electron radiation belt. It is precisely this energy that is shown by electrons causing low-latitude polar light displays. From these data we can conclude that precipitation from the radiation belt actually occurs mainly due to resonant interaction of particles in waves.

Based on these considerations, N. Bryce proposed a space experiment on controlling the precipitation of particles from the radiation belt. The escape of particles from the radiation belt forming polar light displays can be caused on human command. If one increases the concentration of particles in the radiation belt, then one decreases the critical velocity and during precipitation less rapid particles, comprising most of the content of the radiation belt, will participate. N. Bryce proposed introducing into the radiation belt an artificial cold plasma and thereby, using small outlays of energy to form the cold plasma, cause a considerable liberation of energy stored in the magnetosphere.

Estimates show that when the plasma concentration is increased roughly ten times, that is, when it is brought to the rate of ten particles per cubic centimeter, the resonant energy becomes equal to 20-30 keV. This causes particles to be precipitated at the intensity of up to 0.3 erg/cm²·sec. This intensity of precipitation will cause a marked artificial display of polar lights, where the external influence will play the role only of a triggering device. Since barium vapor is easily ionized by solar radiation and one can observe barium plasma, at first glance it is most convenient to have precisely this element participate in the experiment on the force precipitation of particles. Actually, the rapid ionization time of barium (~ 10 sec), extremely convenient when measuring electric fields, is not suitable here since barium vapors cannot significantly expand before total ionization.

/42

The magnetic field blocks further expansion; the magnetic field does not permit the barium plasma to be introduced into the considerable volume occupied by the radiation belt. Injecting a large amount of barium leads to the distortion of the magnetic field, as was observed in German experiments, and forced precipitation due to resonant interaction of waves with particles cannot be isolated in pure form.

Cesium is more convenient for the study of resonant interaction. The ionization time of the cesium atom by solar radiation is ~ 1000 sec, although its ionization potential is less than that of barium. The short ionization time of barium, as indicated earlier, is due to the presence of a metastable level. At the thermal velocities of cesium of about $3 \cdot 10^4$ cm/sec, cesium vapor can up to its ionization be propagated at a distance of 300 km, that is, in injection a ball of cesium plasma 600 km in diameter is formed.

It was proposed to use the American geostationary satellite ARS-1 for injecting the cesium plasma into the magnetosphere. D. Williams was the scientific director of the program. A satellite with a period of rotation around the Earth equal to a day is a geostationary satellite. This satellite is continuously over the same latitude, that is, it is always close to the same force lines of the Earth's magnetic field. The use of a geostationary satellite for injecting cold plasma permits observations by means of instruments onboard the satellite to be made of processes occurring following the injection. For the satellite to revolve synchronously with the Earth, it must be ejected into a circular orbit having a radius that is roughly equal to six Earth radii, that is, the injection of plasma from this satellite must occur along the forced line $L = 6$. It is assumed that the force line associated with the ARS-1 satellite will pass through the ground observation station in Alaska. At the moment of injection much of the force line will be illuminated by the Sun, but the observation station must be in the penumbra. In addition to visual observation of the polar lights and their photography, it is proposed to carry out a series of measurements on sounding balloons and other satellites. Several geomagnetic and radar stations will participate in the measurements. /43

The first attempt to record the forced precipitation of particles from the magnetosphere was undertaken in the experiment of Wescott and coworkers in which the force line was filled with barium plasma from an explosive-type shaped source. Weak precipitation from the force tube $L = 6$ was recorded. However, precisely during this time a magnetic storm was also observed, interfering with observation of the plasma flux, and therefore it remained unknown whether precipitation was caused by filling the force tube with the plasma or by the onset of the magnetic storm.

A similar experiment in a geostationary orbit was proposed by the author of this booklet, using beams of barium ions produced in a stationary-type plasma accelerator. At a 20 A current and barium ion energy ~ 100 eV, which entirely corresponds to the level of present-day equipment, the concentration of the jet in a 1 cm layer is $2 \cdot 10^{14}$ cm $^{-1}$. Assuming the radius of the jet to be equal to the Larmor radius, we get a concentration of ~ 10 cm $^{-3}$.

For an injection lasting 30 min, the force tube will be filled with plasma over a length of $\sim 20,000$ km. These figures are not critical and permit of changes within the limits of an order of magnitude, that is, there is the option, at the experimenter's discretion, of controlling initial conditions. At night there is an excellent opportunity of observing the artificial polar light display against the background of the night sky. The formulation of this experiment does not require special equipment and research methods to be developed.

An experiment in which a force tube was filled with cold plasma can be carried out not only with a geostationary satellite. If the trajectory of the rocket on which the stationary barium plasma source is installed coincides with the force line over the extent of dozens of minutes, and during this entire time the rocket axis is oriented along the field, this flight will also permit the force tube to be filled once by means of the stationary source. /44

Experiments With Artificial Magnetosphere

In the preceding sections experiments were conducted in space aimed at finding the properties of near-Earth space. Most space experiments require careful preparation and can be carried out only with expensive equipment. Exchange for the material and intellectual outlays, space experiments yield unique information on nature inaccessible to ordinary equipment. In spite of all of its cumbersomeness and intensity of work involved, the space experiment is an essential stage of research. However, the unity of the laws of nature make it possible to successfully reproduce in the laboratory some phenomena occurring in the interplanetary medium and in the magnetosphere and to investigate them in conditions familiar to experimenters.

The tremendous difference in the space and time scales imposes definite constraints on the potentialities of laboratory research, but where it is possible to stimulate phenomena, the advantages of laboratory experiments are indisputable. They are simpler, have a broad range of means of investigation, and make it possible to study a phenomenon in the isolated form when it is not masked by an array of complex processes occurring simultaneously.

In a booklet published as part of this same series in 1972, the laboratory experiments on simulating the interaction of solar wind with the Earth's magnetic field have already been discussed¹.

¹ I. M. Podgornyy, Plazma v kosmose i laboratorii /Plasma in Space and in the Laboratory/, Moscow, "Znaniye" Press, 1972.

In this booklet it was stated that by using the principle of constrained simulation, in the laboratory one can reproduce the shape of the magnetosphere with its magnetic tail and the collisionless shock wave induced at the boundary of the magnetosphere when a hypersonic plasma flux flows past it, and in actual conditions the solar wind is this kind of plasma flux. The main parameters of solar wind and the artificial solar wind that is used in model experiments at the Institute of Space Research (ISR), USSR Academy of Sciences, are given in Table 1. /45

TABLE 1

	Velocity, cm/sec	Electron tempera- ture, eV	Concen- tration, cm ⁻³	Field frozen in plasma, Γ
Parameters of solar wind	(3-5)·10 ⁷	20-30	6	10 ⁻⁴
Parameters of arti- ficial solar wind in experiments of the ISR, USSR Academy of Sciences	3·10 ⁷	15-20	10 ¹³	40

The plasma flux in these experiments was directed at a terrella -- a small energized solenoid, a model of the Earth's magnetic field. In these conditions a collisionless shock wave and the shape of the magnetosphere were reproduced. The most graphic idea of how well processes occurring during the flow of solar wind past the magnetosphere are simulated can be given by a spectrum of the magnetic fluctuations at the shock wave front. Fig. 10 shows the spectra of fluctuations obtained in space and in the laboratory. In spite of the fact that these measurements were made independently and the measured quantities differ by many orders of magnitude, the spectra of fluctuation intensities expressed in dimensionless units agree well with each other. The measurements of microfluctuations in the magnetic field in a laboratory experiment with plasma parameters selected on the basis of the principle of constrained simulation are marked in the figure with black dots. The solid line is the intensity spectrum within the shock wave in space plotted from data obtained /46 on an OGO-3 satellite. The open circles, squares, triangles represent measurements taken on the OGO-1 satellite in the turbulent region behind the shock wave front (where the noise

level was somewhat lower than in the shock wave). The density of the magnetic energy in the plasma flux $B^2/8\pi$ was taken as the unit of energy on the graph. The frequency of revolution of the ions along the Larmor circle $\Omega_B = eB/Mc$ was taken as the unit of frequency.

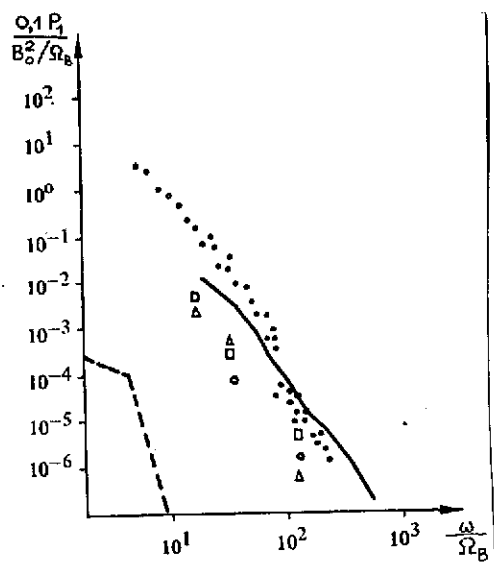


Fig. 10. Spectrum of microfluctuations of magnetic field expressed in dimensionless units. The black circles represent results of simulation experiments. The solid line represents measurements taken in space within the shock wave front. The open circles, triangles, and squares represent different measurements in space behind the front of the shock wave, where the level of microfluctuations is smaller.

percent of the plasma concentration) of fast neutrons, at energies of about 5 keV. The fluxes of electrons penetrating together with the plasma into the magnetosphere were traced by two techniques. Fast electrons striking a scintillating crystal causes it to radiate in the visible spectral region, and this radiation can be recorded with a photoelectric multiplier.

This and a number of other results show that the artificial magnetosphere formed in the laboratory when a plasma flux interacts with the magnetic field of a dipole can be used in studying the physics of near-Earth space. In laboratory conditions active intervention in the processes studied is carried out incomparably more simply. We can say that the laboratory experiment is even a bit too active, since the actual process of measurement in the experiment influences the nature of the phenomenon studied and can lead to significant distortions of the phenomenon. Here it becomes necessary to set up various control experiments aimed at clarifying and eliminating these distortions. /47

A central problem in magnetosphere physics is clarifying the mechanisms by which fast particles enter the magnetosphere. On entering the upper atmospheric layers, fast particles cause the polar lights, a phenomenon incomparable in beauty and splendor. To find the paths of penetration of rapid particles into the magnetosphere, the author together with E. M. Dubinin and Yu. N. Potanin, used artificial solar wind that contains a small population (~ 0.01

Another technique that can produce the intensity distribution of the flux in space is the photographic approach. Sensitive photographic film protected against visible light with a thin aluminum foil is placed in the plane where the intensity of the plasma flux is to be determined. The fast electrons contained in the plasma strike the aluminum foil and drive out x-ray quanta. Quanta at energies of several kilo-electron-volts readily penetrate a 6 micron thick aluminum foil and cause blackening in the photographic film.

The introduction of films of considerable dimensions into the magnetosphere can markedly distort plasma fluxes and the shape of the magnetic field. When a film commensurable with the dimensions of the artificial magnetosphere is used, capable of affording a general idea of the direction of the plasma fluxes, one must carefully select its position so that it does not, as far as possible, overlap the main fluxes and introduces a minimum distortion into the shape of the force lines of the magnetic field. Each such experiment is accompanied by a series of control measurements using miniature fast-electron recording devices and magnetic probes. /48

Polar lights. In the laboratory experiment, it is extremely difficult to observe the glow of gas acted on by particles penetrating into the artificial magnetosphere, but by using various detectors, one can record the same fluxes of charged particles at the surface of a terrella which when entering the atmosphere in space cause polar lights. The precipitation of fast electrons introduced into artificial solar wind were investigated on the surface of a terrella using spherical and cylindrical photographic films. The films were seated on the terrella and were shielded with aluminum foil against exposure to visible light. The blackening of the cylindrical film caused by electron fluxes is shown in Fig. 11. Shown in the same figure is the experimental geometry and a schematic arrangement of the precipitation zones. /49
The main precipitation maximum, observed in the region of the noontime meridian, lies at the high latitudes and continues toward the eveningside, being somewhat shifted into the low latitudes. This precipitation zone spreads also to the morningside, but there the intensity of precipitation is much weaker and the zone is practically invisible in the photograph. /50

In addition to the high-latitude precipitation, low-latitude precipitation is clearly visible. It is separated from the high-latitude precipitation on the dayside and gradually merges with it in the transition to the nightside. Thus, as it were two different ovals of polar lights are observed, which overlap on the nightside. Processing of measurements for the eveningside is shown in Fig. 12. This pattern is characteristic of both the northern as well as the southern hemispheres.

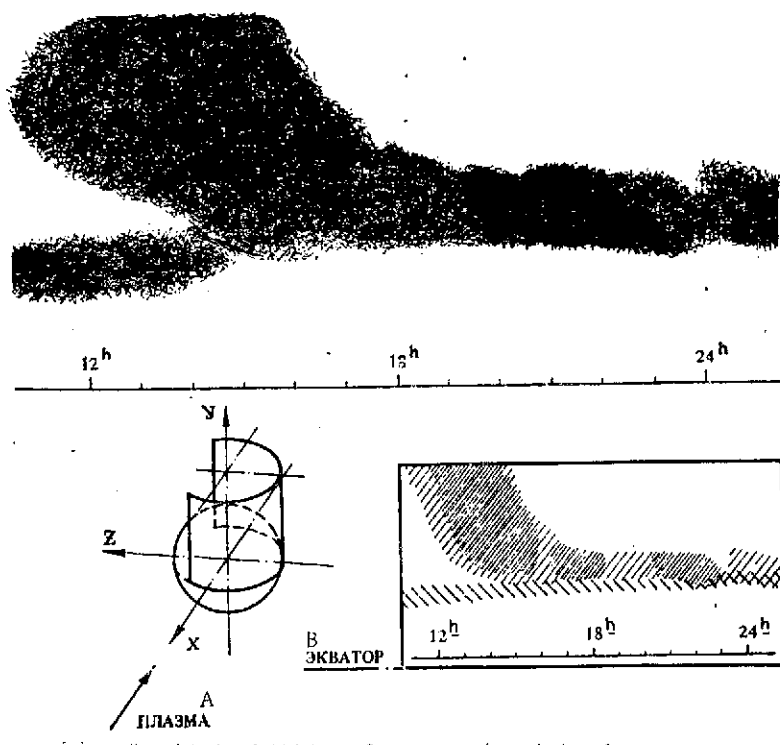


Fig. 11. Photograph of cylindrical film seated on terrella, and its exposure scheme. Two zones of particle precipitation can be seen on the dayside. The high-latitude zone was formed due to plasma breaking through the north polar cusp. Electrons precipitated from the radiation belt in the low-latitude zone.

KEY: A. Plasma
B. Equator

In spite of the many years of investigation of polar lights, 50 information on their distribution by latitude is inadequate and thus far there is no widely accepted model of the distribution of their intensities. Sometimes one speaks of a single oval girdling the Earth; recently the view that two independent ovals exist has become more current.

Quite often the oval shape of the polar lights is not accepted and views of the different origin of particle precipitation on the dayside and the nightside are expressed.

A wealth of material on the precipitation geometry of charged particles, collected during measurements on spacecraft, was generalized by N. Bryce and T. Hartz. The results of this generalization is shown in Fig. 13. In the model of N. Bryce

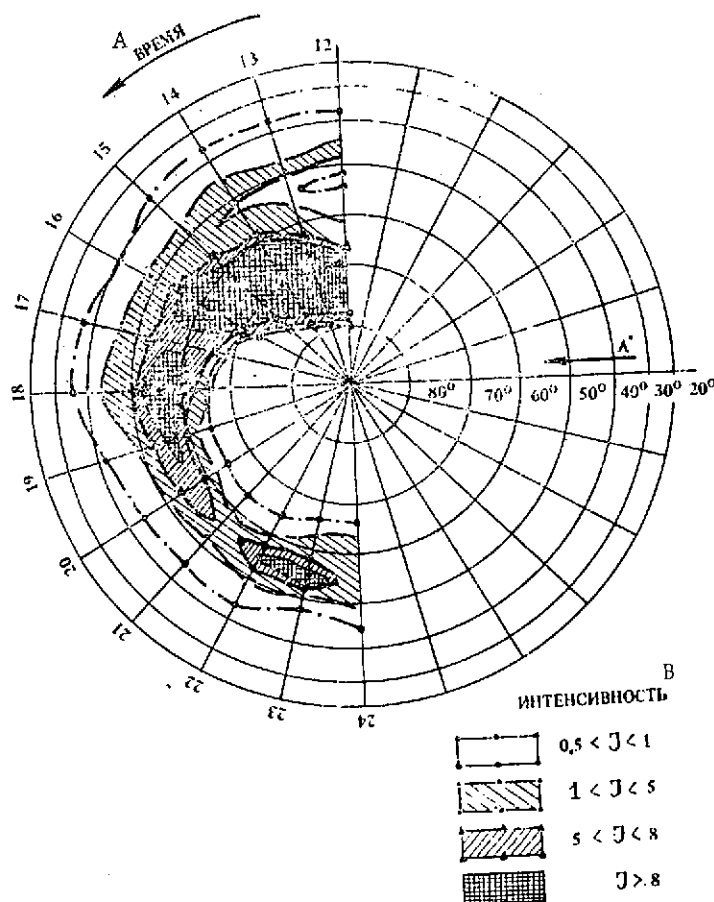


Fig. 12. The intensity of particles precipitating on the eveningside, obtained in the model experiment.

KEY: A. Time
B. Intensity

produced by an energized coil, and directly at the surface of the coil the configuration differs from the dipolar. The terrella field is closely described by the formula of the dipole field only at a distance that is several times greater than the characteristic dimension of the coil, while the Earth's magnetic field, where the field source lies deep in the Earth's interior, at the surface is already virtually dipolar. Thus, the model experiment showed that there are two oval precipitation zones, which is in agreement with the Bryce-Hartz model plotted on the basis of

Polar lights in nature, and in laboratory conditions of photographs of precipitation at the terrella surface can be viewed as the result of the action of some unique television

and T. Hartz we can clearly see two particle precipitation zones on the dayside, which smoothly grade into the nightside and there merge. The picture given by N. Bryce and T. Hartz, plotted from individual measurements taken at different times, agrees with the data of the model experiment (Fig. 12), which are "simultaneous" in nature, that is, they yield the total pattern of precipitation for a specific instant of time.

The only difference between the distributions of precipitating particles in space and in the laboratory is the non-coincidence of the absolute values of the precipitation latitudes. This deviation is not of fundamental importance and is due to the fact that the magnetic field of the terrella is

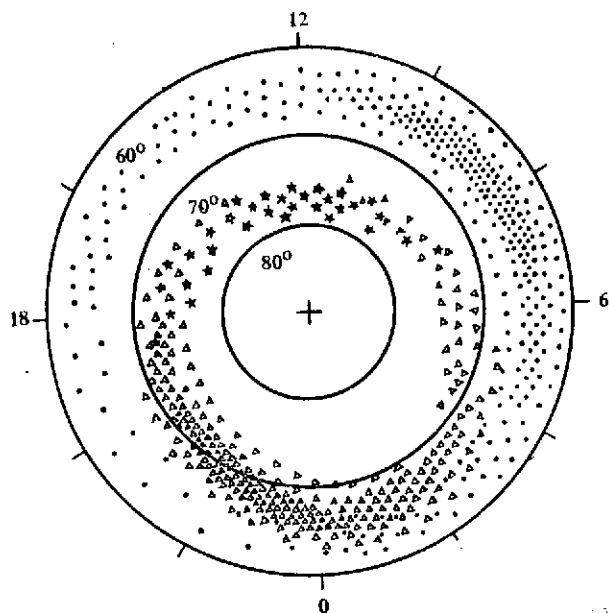


Fig. 13. Precipitation of particles plotted by Bryce and Hartz based on a set of measurements in space.

noontime meridian and its existence was not entirely unexpected. During a magnetohydrodynamic examination of solar wind streaming past the Earth, two neutral points lying at the noon meridian were obtained at the surface of the magnetosphere. The field direction is not determinate at these points, and a particle arriving from the solar wind can penetrate the magnetosphere, since its adiabatic invariant is not preserved in the region of the neutral point.

In actual conditions, there is no mathematical neutral point, since there can never be an infinitely thin idealized boundary between the plasma and the field, and one can expect a considerable breakthrough of the plasma flux along the interface of force lines exiting to the tail from the lines forming the close magnetosphere. This configuration of a magnetic field was investigated in the laboratory long before the existence of the boundary of the magnetosphere became known. In experiments with magnetic thermonuclear traps, the author showed that the plasma flux spreads apart the magnetic field force lines and can easily penetrate into the strong-field region. The possibility of particles penetrating the magnetosphere in the region of the supposed existence of neutral points was first pointed out by G. A. Skuridin /53 and coworkers.

system giving a kind of transformed image of physical processes in the magnetosphere. It is especially convenient to interpret the image in conditions of laboratory experiments.

Polar cusps in the magnetosphere. Laboratory experiments in 1970 at the ISR of the USSR Academy of Sciences and the data of space measurements by L. A. Frank showed that there is a very clearly pronounced breakthrough of particles into the magnetosphere on the dayside at the point where the force lines of the polar cusp and the force lines of the closed magnetosphere separate. The breakthrough of particles was detected near the

Measurements made with an artificial magnetosphere showed that the high-latitude precipitation is directly associated with the breakthrough of plasma along the boundary of the polar cusp. Detailed studies concluded that the region of breakthrough is not localized on the dayside, but extends over to the nightside. By placing a film in various meridional sections of the artificial magnetosphere, one can establish both the shape of the region of particle incursion as well as the direction of the invading flux to as far as its survival at the surface of the terrella. The regions of invasion encircle the entire terrella and are deep cusps along which particle fluxes arrive at the precipitation zones. One of these polar cusps lies in the northern hemisphere, and the other -- in the southern. Each of the cusps delimit the bundle of force lines leaving the corresponding polar cusp into the geomagnetic tail.

Studies conducted directly in space thus far have not produced adequate data on the shape of the polar cusp but where information is available, it agrees fully with results of laboratory experiments. For example, measurements by W. Heikkilä showed that the polar cusp, or as he phrased it, the "rift", extends toward the evening and morningsides by at least ten degrees.

A cross section of the cusp in the plane of the principal meridian is shown in Fig. 14. The boundary of the magnetosphere impenetrable for the artificial solar wind can be readily seen. At this boundary the pressure of the plasma flux is equalized by the pressure of the magnetic field. In the region of the "neutral point" the plasma flux enters the magnetosphere and then arrives at the surface of the terrella, producing the high-latitude precipitation zone. A similar penetration can be clearly seen on the nightside as well.

We should point out once again that introducing a film cassette into the plasma flux can distort the streamline pattern, therefore each photograph was carefully checked with measurements taken using magnetic probes and miniature films placed in different locations. Since the plane of the noon and midnight meridians is 54 a plane of symmetry and does not intersect the flux of the artificial solar wind, the distortions introduced by the film cassette proved to be virtually undetectable. In spite of the fact that the distortions introduced by the films placed in the other meridional sections proved to be greater, by using the series of photographs the continuous region of incursion could be traced -- the polar cusp girdling the terrella. On the nightside the cusp is directed nearly perpendicular to the magnetic action of the dipole and is somewhat displaced toward the equator. The particles rushing through the northern and southern polar cusps then form high-latitude precipitations in both hemispheres. Since on the nightside the polar cusps are closer to the equator than on the dayside, the high-latitude precipitation also lies there closer to the equator and merges with the low-latitude precipitation. The pattern of the low-latitude precipitation was clarified in another series of model experiments.

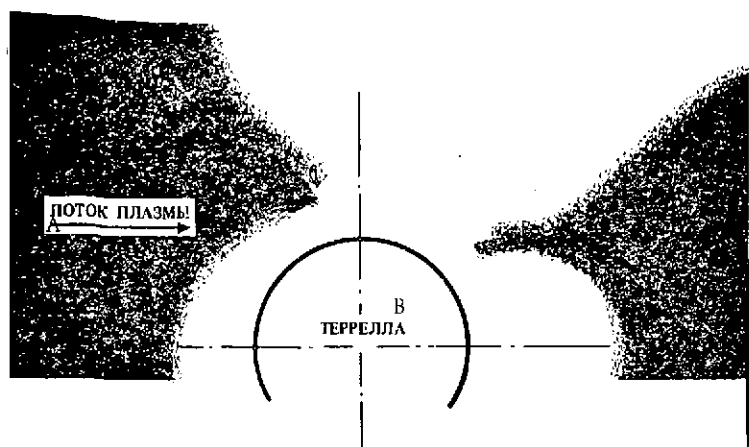


Fig. 14. Photograph of section of artificial magnetosphere in the plane of the principal meridian. Clearly visible is the boundary of the magnetosphere. There are regions of plasma penetration on the dayside and nightside. They represent a unified polar cusp!

KEY: A. Plasma flux
B. Terrella

Low-latitude precipitation and radiation belt. The very first laboratory experiments with an artificial magnetosphere showed that low-latitude precipitation cannot be linked to the penetration of particles into the polar cusps, and one must seek another mechanism of formation of this precipitation. Measurements of the spatial distribution of fast neutrons showed that in the magnetic field of an artificial magnetosphere there are trapped fast electrons, which on drifting along the dipole axis form the radiation belt. The electrons trapped by the magnetic field are

reflected from the mirror points; however some of them exit along a force line and precipitate at the surface of the terrella. It is precisely these electrons leaving the radiation belt that produce the low-latitude precipitation zone.

The escape of particles from the radiation belt is not unexpected, since there are a number of processes causing the disruption of the adiabatic invariant and the escape of a particle along a force line. One mechanism of the disruption of adiabatic invariance associated with the resonant interaction of a wave with a particle was examined in the preceding section. It is much harder to account for the trapping of particles in the magnetic field. If the trapping of protons by the Earth's magnetic field can be satisfactorily accounted for by the radioactive decay of neutrons, that is, by the formation of charged particles directly in a magnetic field of trap configuration, it was not possible earlier to find an effective capture mechanism for the electrons.

The artificial magnetosphere offers the possibility of nearly unlimited variation of conditions, and in particular, it makes it possible to introduce partitions into the radiation belt and thereby to determine the position of a fast-particle source. An array of a large number of experiments with partitions showed that filling of the radiation belt with electrons occurs on the night-side. Partitions placed on the nightside in both the planes of the meridian and the equator completely eliminate the radiation belts. The entire low-latitude zone of particle precipitation on the terrella surface also disappears simultaneously. /56

Partitions placed at other latitudes halt the precipitation and remove the radiation belt in the sector enclosed between the partition and the noon meridian toward the side of electron drift from the partition position. In the rest of the magnetosphere, that is, in the sector lying on the side of the electron drift from the night meridian, the nature of particle precipitation and concentration in the radiation zone remains unchanged, as far as can be seen. Thus, partitions placed at any location except for the noon meridian interrupt the drift of electrons around the dipole axis extending from the nightside. When a partition is placed on the nightside, the arrival of electrons into the radiation zone is entirely halted. One must especially emphasize that the precipitation of electrons from the radiation belt occurs only in the low-latitude zone.

Experiments with partitions intersecting particle fluxes in the radiation belt in natural conditions can be carried out in the magnetosphere of Jupiter. Some of Jupiter's natural satellites lie within the magnetosphere, and as they move around the planet they must overlap fluxes of trapped radiation at different longitudes. A paper by W. Hess noted that the presence in Jupiter's magnetosphere of natural satellites permits measuring the radial diffusion of particles in the radiation belts. Recent data of model experiments of radiation belts filling on the night-side show that investigations of Jupiter's magnetosphere on spacecraft are becoming particularly vital. During the flyby of the American spacecraft Pioneer 10 past Jupiter a radiation belt was found. When Pioneer 10 transected the satellite orbits, a drop in the fluxes of trapped particles was observed. Thus far it is not clear whether these data obtained in a single flight of a spacecraft permit the conclusion that fast-particle sources are localized in Jupiter's magnetosphere.

Model of the magnetosphere. The use of different methods of investigating the artificial magnetosphere made it possible, in addition to the polar cusps, to also detect the equatorial cusp. The equatorial cusp is not manifested in the noon meridian, but it begins not far from it. On the morning and eveningsides the plasma flux presses, close to the equator, on closed magnetosphere lines and it penetrates into its convex boundary. The /57

farther toward the nightside, the more strongly the plasma flux presses on the force lines and the deeper the cusp becomes, but its depth remains less than the size of the magnetosphere and penetration across the equatorial gap does not reach the inner regions of the magnetosphere. On the nightside the equatorial cusp grades into the plasmashet. In this sense the equatorial cusp must be viewed as an extension of the plasmashet on the dayside. Since the equatorial cusp begins at the evening and morningsides, it is not visible in the cross section of the magnetosphere along the principal meridian (Fig. 15). The figure schematically shows the position of the radiation belt and the two precipitation zones: the low-latitude and the high-latitude zones.

On the nightside of the profile are shown several regions differing in physical content. First there is the internal region -- the closed magnetosphere with boundary B_M . Solar wind plasma does not stream more deeply than the boundary B_M and here there are only fast radiation-belt particles. High-concentration plasma adjoins the outer side toward B_M . The parameters of this plasma do not differ strongly from the parameters of the plasma breaking through the dayside of the polar cusps. The outer boundary of the high-concentration plasma S extends through point X, at which the direction of the vertical component of the magnetic field changes. The curve S can be viewed as a separatrix/transported to the nightside, dividing the polar-cap force lines from those of the closed magnetosphere. Plasma enclosed between B_M and S arrive from the part of the polar cusp that adjoins the closed force lines. Beyond the line S lies the low-concentration region of the plasma trailing off into the tail. The plasma enters this region from the parts of the polar cusp lying closer to the polar cap. Finally, on the nightside there is a plasma-free region formed by force lines (arriving from the polar cap) producing the geomagnetic tail. Above the equatorial plane they are oriented toward the Sun, while below the equatorial plane 58 they are oriented from the Sun.

The magnetosphere model obtained from laboratory data, more exactly, a model of the magnetosphere cross section in the noon-midnight plane, agrees with a number of individual space measurements. For example, the possibility of variation of the sign of the vertical component of the tail field (that is, the existence of a neutral line intersecting the figure at point X) was repeatedly discussed in the literature in relation to experimental data obtained on spacecraft. The nonstationary nature of magnetic effects in the tail does not thus far permit a clear regularity of localization of the neutral line to be established. The change in its position is often linked to the onset of a magnetic substorm.

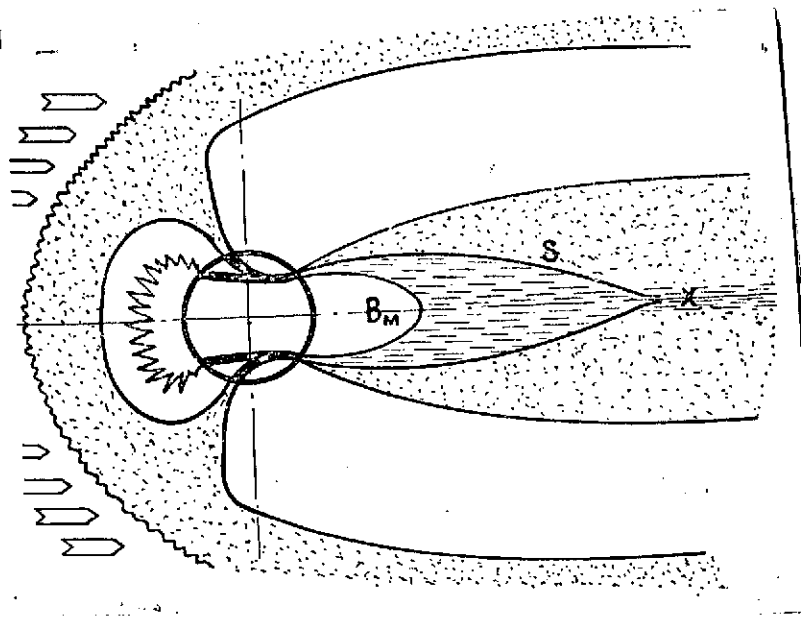


Fig. 15. Scheme of magnetosphere profile along the midnight-noon meridian. At point X the neutral line intersects the plane of the drawing. Between B_M and S lies the high-concentration plasma arriving together with force lines convected along the magnetosphere boundary.

Now let us examine how the equatorial profile of the magnetosphere appears (Fig. 16). Owing to the shortage of space measurement data, we will use only the results of model experiments. A plasma flux streaming past the magnetosphere penetrates more and more deeply into the equatorial cusp and then penetrates into the plasmasheet of the geomagnetic tail. The equatorial penetration indicates that strong interaction of the plasma flux with the magnetic field exists, leading to entrainment by the flux of the magnetic field force lines. The force lines entrained by the flux, more exactly, their projections onto the equatorial plane, are shown as curved in the direction of motion or, as is more commonly expressed, in the direction of the convection. The force lines transported to the nightside due to convection are stretched by the plasma flux. Two fluxes meet on the nightside. One arrives from the eveningside, and the other from the morningside. Interaction of the fluxes occurs in the region denoted in Fig. 15 by the curves B_M and S. Plasma theory examined several cases of instability of two-flux motion. Fluxes bearing magnetic fields interact especially strongly. Upon interaction of fluxes, microfluctuations arise, which in turn lead to an increase in the effective frequency of collisions between plasma particles. The

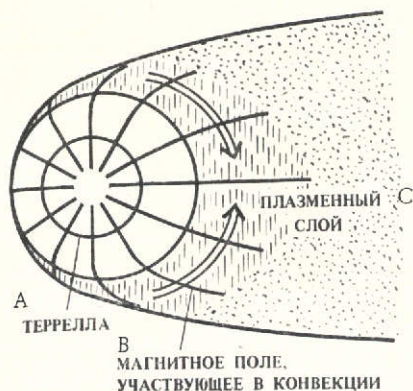


Fig. 16. Scheme of magnetosphere cross section cut by equatorial plane. The plasma "streaming" into the equatorial cusp entrains the force lines and transports them to the nightside. In the cusp the lines are shown curved in the flux direction.

KEY: A. Terrella
B. Magnetic field participating in convection
C. Plasmasheet

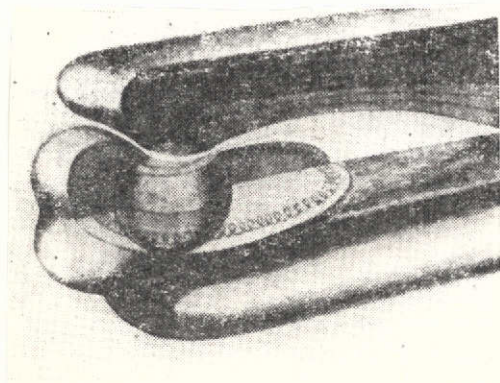


Fig. 17. Model of magnetosphere constructed on the basis of laboratory experimental data. The annular polar cusp enables particles to penetrate into the high-latitude zone of polar lights. The radiation belt can be seen in the profile. The escape of particles from it causes polar light displays in the low-latitude zone.

increase in collision frequency means a reduction in electrical conductivity, and the force lines /60 cease to be plasma-bound. They are shortened and are buried within the magnetosphere. The individual fast particles that are buried in the magnetosphere together with the force lines provide the beginning of the radiation belt. Thus, the convection of force lines in the boundary layer and the interaction of the incident plasma fluxes lead to the appearance of the source of radiation-belt particles near the midnight meridian.

A three-dimensional magnetosphere model is shown in Fig. 17. Easily seen is the northern polar cusp encircling the terrella, and the equatorial cusp beginning on the dayside. Within the cut can be seen the radiation belt. It should be stressed once again that this model was constructed from laboratory data and some of its details require confirmation and space. The data of Heikkila (United States) and K. I. Gringauz and coworkers (USSR) show that polar penetration is extensive, thus far there are no measurements in space confirming the "girdling" of the Earth by the polar cusp. Thus far nothing is known about the existence of an equatorial cusp in the Earth's magnetosphere if one does not consider qualitative considerations (Ya. I. /61 Fel'dshteyn) based on indirect data.

The model shown in Fig. 17 makes it possible to most economically plan the trajectories of spacecraft designed for investigating the magnetosphere.

Conclusions

In the preceding sections we examined experiments in space using fluxes of charged particles and plasma artificially introduced into the Earth's magnetosphere. Space experiments are often called active or controlled in order to underscore that when they are carried out there can be qualitative changes in the state of space, in distinction to measurements of parameters of the magnetosphere and interplanetary media when distortions introduced by a craft must be at a minimum. Besides the plasma, probing with electromagnetic radiation is being successfully used in influencing the magnetosphere. For a number of years, Professor V. A. Troitskaya, together with French colleagues, has been successfully investigating the propagation of electromagnetic disturbances along a force line of the Earth's magnetic field. The measurements are taken simultaneously at two stations located on the same force line. In Arkhangel'skaya Oblast the research is being carried out by Soviet scientists, and on Kergelen Island -- by French scientists. Noteworthy is the proposal to initiate the precipitation of particles from the magnetosphere with a generator of electromagnetic vibrations (R. A. Halliwell, United States).

A few remarks should be made on the proposal of S. M. Krimigis to vaporize several dozens of kilograms of lithium in the solar wind in front of the Earth's shock wave. By tracing lithium isotopes and by measuring their energy at different points in the magnetosphere, one can find the place of acceleration of precipitating particles and the paths of their penetration into the magnetosphere. Preliminary data showing that particles arriving from solar wind participate in polar light displays were recently obtained by the analysis of the isotopic composition of helium in the solar wind and the polar light displays. In these experiments, use was made of an ingenious method of absorbing particles using foils, developed by I. Hayes. /62

Data on the makeup of the solar wind were obtained by exposing aluminum foils unfurled on the Moon surface by Apollo spacecraft crews. After being exposed to solar wind flux, the foils were brought to Earth and the composition of the absorbed material was studied. The Moon is an ideal "laboratory" for solar wind study, since it has neither atmosphere nor its own magnetic field and therefore is not protected against the plasma flux coming from the Sun. Among other data, the ratio of the isotopic composition of helium in the solar wind were obtained by the foil method. It turned out that the ratio of concentrations of the isotopes He^3 and He^4 is $\sim 4 \cdot 10^{-4}$. In the Earth's atmosphere this ratio is $\sim 10^{-6}$. If one measures the isotopic composition of helium in a flux of fast particles causing polar light displays, one can find whether these particles come from the solar wind or whether they are formed by the acceleration of magnetosphere ions.

To determine the relative concentration of helium isotopes in the flux causing polar light displays, rockets bearing folded aluminum and platinum foil in a hermetically sealed container were launched into the zone of the polar lights. At an altitude of about 200 km the foils were unrolled and exposed for about 20 sec. Although the exposure time was short and the measurement precision proved to be only moderate, the data afforded the conclusion that auroral particles evidently arrive from the solar wind, which is in agreement with the magnetosphere model constructed on the basis of laboratory experimental data.

Space experiments are becoming increasingly rich in content. It is possible that the time will come when we will learn to control the processes in the magnetosphere which are the most important for the national economy. For example, the precipitation of fast particles in the atmosphere alters its composition at high altitudes, and therefore also the transparency in different spectral regions. If precipitation processes become controllable, the nearly unlimited possibility of regulating weather on a global scale will open up.